FACTORS AFFECTING THE DETERMINATION OF DENSITY AND MOISTURE BY NUCLEAR RADIATION TECHNIQUES

JULY, 1963

NO. 18

Joint Highway Research Project

by

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Progress Report

FACTORS AFFECTING THE DETERMINATION OF

DENSITY AND MOISTURE BY NUCLEAR RADIATION

TO: K. B. Woods, Director
Joint Highway Research Project

May 15, [illegible]

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 6-10-5
Project: [illegible] 16E

Mr. Matthew [illegible] has prepared the attached Progress Report entitled 'Factors Affecting the Determination of Density and Moisture by Nuclear Radiation'. Professor E. J. Yoder [illegible] the research which is reported here. Mr. [illegible] also used the research reported for his MSCE thesis.

This report contains the results of a laboratory investigation of various factors that influence the determination of density and moisture of soils by nuclear radiation techniques which utilize the [illegible] principle. The investigation of use of radioactive techniques for moisture and density measurement is continuing.

This report will also be forwarded to the Bureau of Public Roads through the Indiana State Highway Commission for their review and comments inasmuch as this research was performed as an HPS project.

The report is presented for the record.

Respectfully submitted,

[illegible]
Harold L. Michael, Secretary

HLM:bc

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Progress Report

FACTORS AFFECTING THE DETERMINATION OF DENSITY AND MOISTURE BY NUCLEAR RADIATION TECHNIQUES

by

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File No: 6-10-5

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May 15, 1963

ACKNOWLEDGMENTS

The author sincerely expresses his gratitude to Professor Eldon J. Yoder, who patiently guided and advised in times when endeavor and endurance were most needed.

Grateful acknowledgment is made for the assistance to the research project by the Joint Highway Research Project of Purdue University, Professor K. B. Woods, Director, and financial assistance obtained from Purdue University.

The author expresses his gratefulness to all those who contributed to completion of the project. Also, the critical review of this text by Professor V. Bergdolt of the Nuclear Engineering Department is acknowledged.

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ABSTRACT

Witczak, Matthew, M.S.C.E., Purdue University, June 1963. "Factors Affecting the Determination of Density and Moisture by Nuclear Radiation Techniques". Major Professor: Eldon J. Yoder.

This report contains a laboratory investigation of various factors that influence the determination of density and moisture by nuclear radiation techniques that utilize the backscatter principle.

A total of five materials were tested in the research program. These materials were subsequently divided into two material groups. This was done as an aid in employing different procedures of testing to the groups. For one group, a system of built-up material layers was tested for a given type. The last group of tests were performed on several gradings of a crushed limestone and a siliceous gravel.

It was concluded that material type is a factor which influences nuclear density determinations. For the moisture unit, material type had no effect upon count readings for all materials tested. Grain size distribution influenced nuclear density readings for a given material type. Effect

of moisture in the substrate material upon density readings was considered negligible for the range in moisture quantities studied.

Generally, instrument stability was a function of the instrument in question. Adverse effects of temperature were negligible for density and moisture self-standards for Instrument A, while Instrument B was found to be inoperative at a temperature of 0°F. Instrument A deviations in density counts per minute were considered to be adverse for battery supply voltage conditions, however the use of a count ratio procedure eliminated this deviation.

It was found that extreme care must be taken to insure that physical conditions surrounding the density gages are the same when taking self-standard readings at different times. If this is not observed, validity of results obtained are questioned even though a count ratio procedure is used tc analyze the data. The introduction of a leveling course had greater effect on the density results obtained on the open graded materials than on those for the finer crushed materials.

INTRODUCTION

The determination of the soil density and moisture content is of the utmost importance to the Civil Engineer. Likewise, the speed, accuracy, and reliability of the actual measurements are also of extreme importance.

In the past several years, a new method of measuring soil density and moisture was developed through the use of radioactive attenuation. This method was developed on the nuclear physics' principles that the attenuation of gamma rays is dependent on the density of the material and fast neutrons can be directly moderated by the presence of water.

However, the applications of radioactive scintillation methods to soil density and moisture measurement have been limited because of uncertainties regarding methods of calibration. Accuracies obtained from field usage based on a single manufacturer's curve have been questioned by some investigators. In fact, difference in viewpoints have been expressed as to the true connotation of accuracy as applied to soil density and moisture measurements.

But in all eventualities, the nuclear system of soil measurement is in its infancy. Undoubtedly, limitations stemming from various factors are imposed on the usage of the equipment at present. However, through the combined skills of the scientist and the engineer, the applications will widen and the limitations will diminish.

REVIEW OF LITERATURE

Historical

The discovery of a neutral particle to possess the capability of ejecting protons from a paraffin block by collision was made by Sir James Chadwick in 1932. In 1920, E. Rutherford suggested the presence of this particle, which he called a neutron; however, it wasn't until Chadwick's work in the 1930's before the first direct evidence of its existence was established.

As time progressed, research teams soon became cognizant of the neutron moderating facility of the hydrogen atom and consequently water. In the late 1940's the Civil Aeronautics Administration set forth the first attempt to establish soil density and moisture by nuclear methods in the United States. Contracts were given to Cornell University to establish the adaptability of nuclear techniques to soil measurement.

Pieper (1), Krueger (2), and Belcher and Cuekendall (3) investigated the problem and the results were favorable. Feasibility of nuclear techniques was established but limited in nature due to the lack of portable instrumentation. However, improvements were soon devised by Carlton (4) in 1953, and by Roy and Winkerkorn (5) in 1957. In 1956, Pocock (6) developed the mathematical analysis for portable gamma-ray surface density gages for the Michigan State Highway Department. The analysis soon became a reality as the Michigan nuclear combination density-moisture surface gage was introduced in 1959 (7).

Eventually, as knowledge of electronics increased, rapid development was accomplished not only in the United States, but in several foreign countries. Commercially, portable units have been on the market for 6 years and as time lapses, continuous improvement of already existent gages matures at an ever increasing pace.

Theory

Principles of Moisture Gage

The theory of neutron moderation for soil moisture measurement is dependent upon several physical facets. These are: the presence of fast neutrons, the ability for hydrogen (water) to moderate or slow down the fast neutrons, and the existence of detection devices to measure only these slow neutrons.

In the moisture gage, a radioactive source emits fast neutrons into the soil substrate, where they may be either absorbed or moderated to a lower energy level. Hydrogen has the property of being both a low absorber and a highly effective moderator. Consequently, hydrogen possesses one of the highest neutron moderation capabilities of all elements. As the slowed down neutrons backscatter in all directions throughout the substrate, some of them are transmitted to the detecting device, ionized, and sent as a pulse signal to a recording device called the scaler. Since the moderation is dependent upon the amount of hydrogen present in a volumetric zone of influence, results are calibrated against the weight of hydrogen (water) present in a certain volume; ususally taken as a unit volumetric measurement.

Principles of Density Gage

Nuclear density units can be classified into two types: direct transmission and surface backscatter gages. Since both Instrument A and Instrument B are of the latter case; the following discussion is primarily related to the theory employed in the surface backscatter gage.

The theory involved in the operation of the backscatter device is extremely complex. As the photons penetrate into the soil substrate, they can either be absorbed by the mass (Photo Electric Effect) or can collide with a loosely bound electron and scatter a reduced energy photon in a different direction. (Compton Effect)

The concept introduced for these relativistic quantum effects for expressing that any of these possibilities will happen is the cross section σ. The cross section represents an area which is proportional to the probability of an event taking place. If the number of atoms per unit volume is represented by n ; then the linear absorption coefficient μ is the product of η & σ or: $\mu = \eta\sigma$ The units of the absorption coefficient μ are length^{-1}. If the linear absorption coefficient is divided by the weight per unit volume of the material, a mass absorption coefficient μ_m for the material is defined ($\mu_m = \frac{\mu}{\gamma_m}$). The units are length^2 x mass^{-1} for the mass absorption coefficient.

The equation governing the intensity of a parallel beam of photons passing through an absorber of thickness t can be represented by: $I = I_o e^{-\mu t}$ where I_o is the intensity of radiation incident to the absorber, and t is the thickness of the absorber. If the linear absorption coefficient, μ is replaced by $\mu_m \gamma_m$, then the general equation relating intensity to substrate density is defined as:

$$I = I_o e^{-\mu_m \gamma_m t}$$

For the Compton Effect, a mathematic model was created and experimentally justified by Carey and Reynolds (6) and (8). The expression $I = k_1\gamma + k_2\gamma^2 + k_3\gamma^3$ represented the intensity recorded from a gage put on a material with an infinite number of electrons available for collisions but no absorption (8).

Since these relationships cannot exist independently of each other, due to a resulting absorption increase as the number of electrons increase; the combined intensity was stated as the product of the two effects, or: $I = I_o e^{-k_4\gamma} (k_1\gamma + k_2\gamma^2 + k_3\gamma^3)$ where k_1, k_2, k_3, k_4 represent manufacturer's design constants(8). The last relationship, in essence, demonstrates the feasibility of adopting physical principles to the employment of commercial gages to soil density. Experimental tests results have verified the expression, and it has been found that in the realm of typical soil densities, the intensity of back scatter radiation is a linear inverse proportion of the measured substrate density(6).

Summary of Physical Principles

An all important fact, perhaps overlooked in the application of the nuclear measuring devices, is that the backscatter radiation of the unit is not a direct measure of the physical soil parameters of density and moisture. Rather, it is a measurement of physical principles which can be correlated, not totally, to the soil parameters in question. Complete dependency upon soil density and quantity of water in a soil mass as the physical principles will possibly lead to discrepancies for both gages. An investigation of several variables introduced by material type that may influence the density and moisture determinations is presented in the Discussion of Results of this thesis.

PURPOSE AND SCOPE

The purpose of this study was to investigate various factors affecting the nuclear density and moisture results in laboratory tests. Two instruments were employed in the research program; however, no attempt was made to correlate the performance of one instrument with the other.

The selection of variables used as the foundation for the testing were categorized into: substrate material properties, instrument stability, and procedural factors. There is little doubt that the variables categorized in each group are not all inclusive or complete in their nature. However, it is felt that the major possible causes of variances in test results were investigated.

For the category of substrate property effect, three variables were introduced. These were material type, presence of moisture in the sample,and grain size distribution.

Also involved in this category was an investigation relative to the determination of the effective depth of penetration for density and moisture.

For investigations pertaining to instrument stability, system checks were completed on the adverse effects of battery voltage, timer accuracy, and the effect of temperature upon count readings. Also, aging effects of the instrument were studied through the use of periodic voltage plateau curves.

The variable of procedure includes methods of expressing final results as well as procedures employed in the determination of count readings. Tests reflecting the reliance of self-standards were accomplished to determine their repeatability as instrument checks. The use of self-standards in expressing results as a count ratio was made. Effects upon density count readings when using a leveling course between the instrument and material were studied. Finally, densities were calculated by bulk volume methods and correlated with sand cone densities.

MATERIALS

A total of 5 different materials were tested with two commercial nuclear instruments. The materials were:

I. Material Group I

   A. Coarse Sand

   B. Sand-Soil Mix

   C. Sandy Gravel

II. Material Group II

   A. Quartzite

   B. Limestone

For the materials in group II, a total of three grain size distributions were used for both the quartzite and limestone; with physical data appearing for only gradation III.

Figures 1, 2, and 3 show the standard AASHO compaction curves and grain size distribution curves, respectively. Table 1 summarizes the physical data of the materials studied, while Table 2 presents a quantitative analysis for the limestone and quartzite.

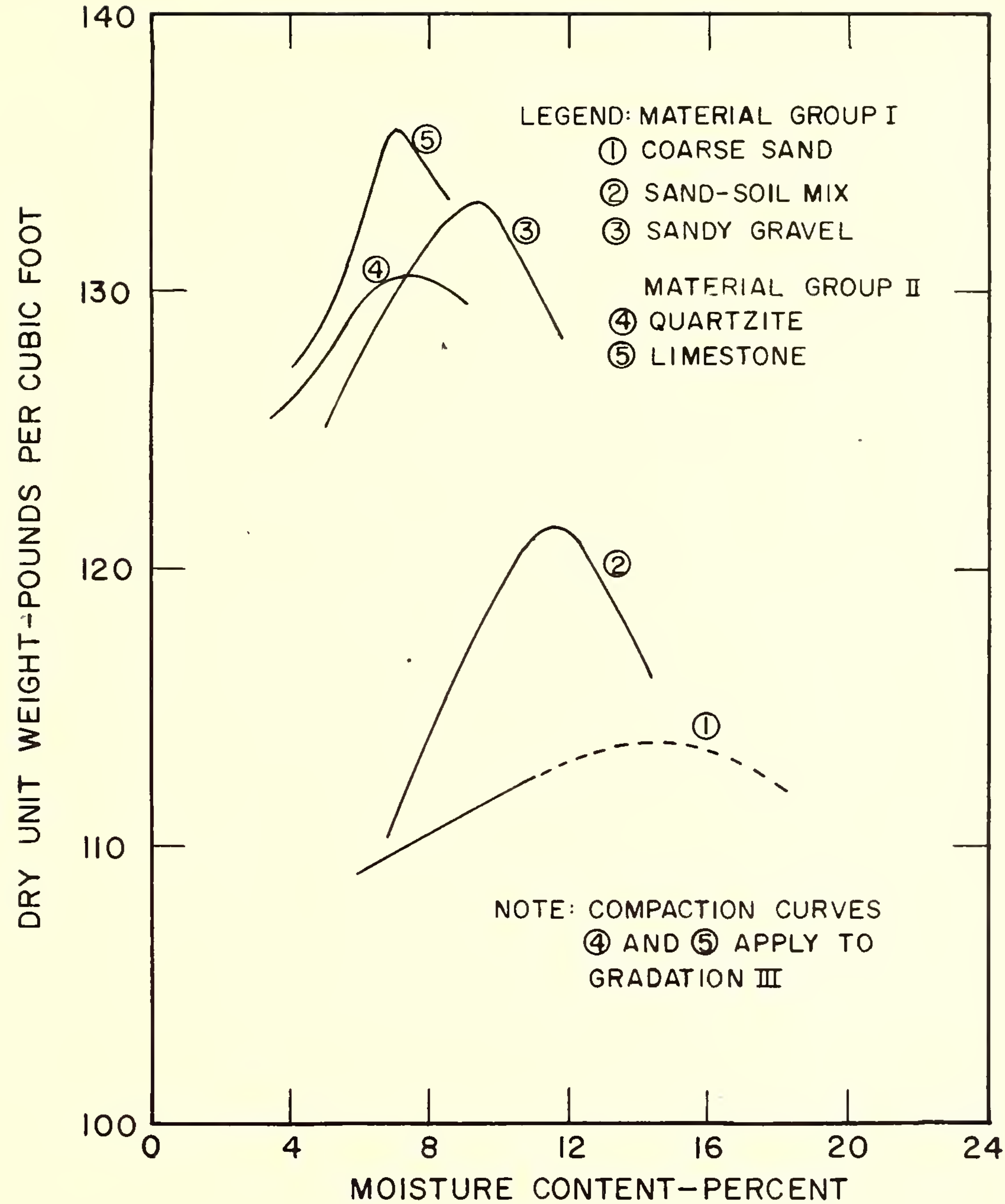

FIG. I STANDARD AASHO COMPACTION CURVES

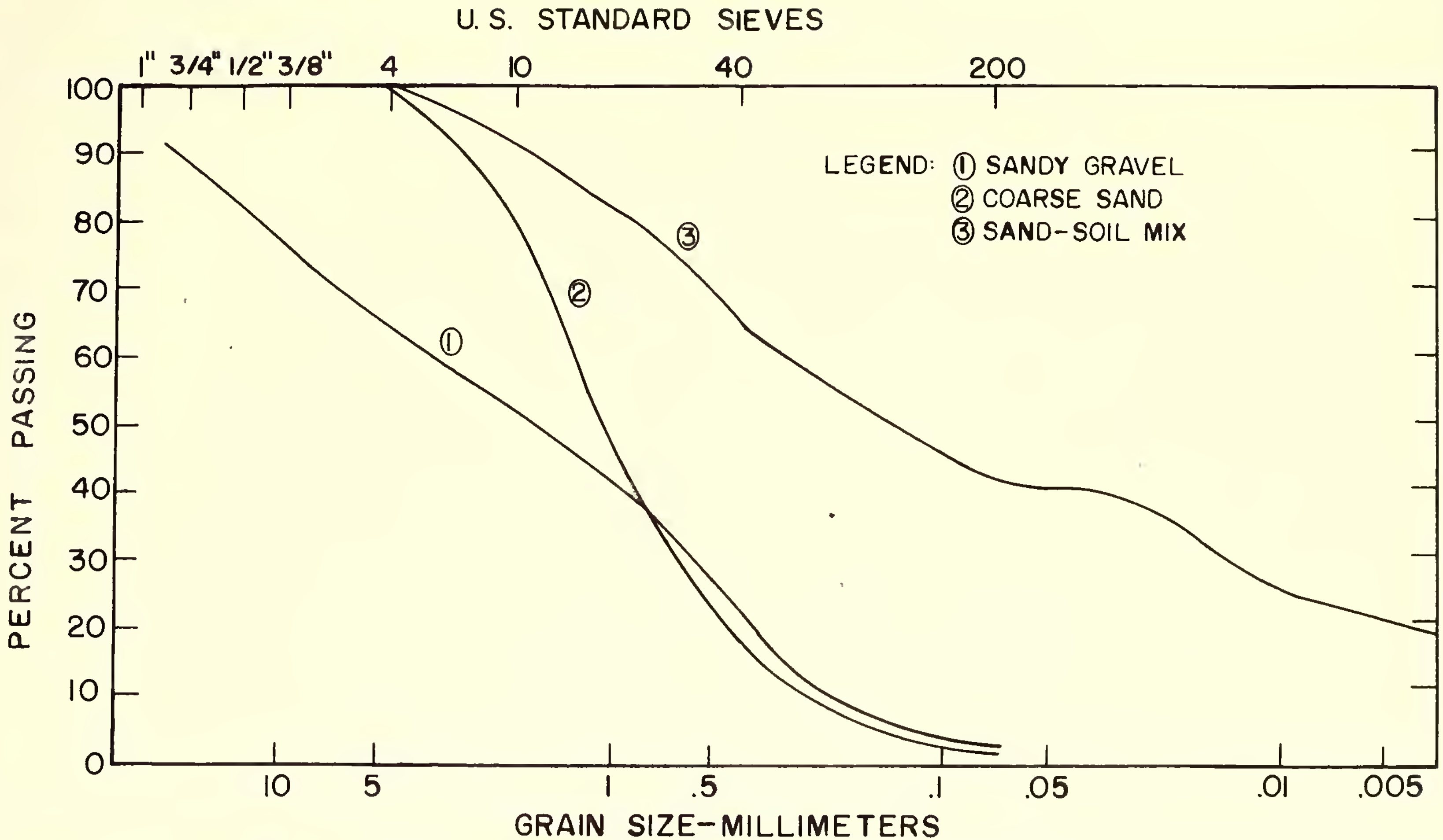

FIG. 2 GRAIN SIZE DISTRIBUTION CURVES OF MATERIAL GROUP I

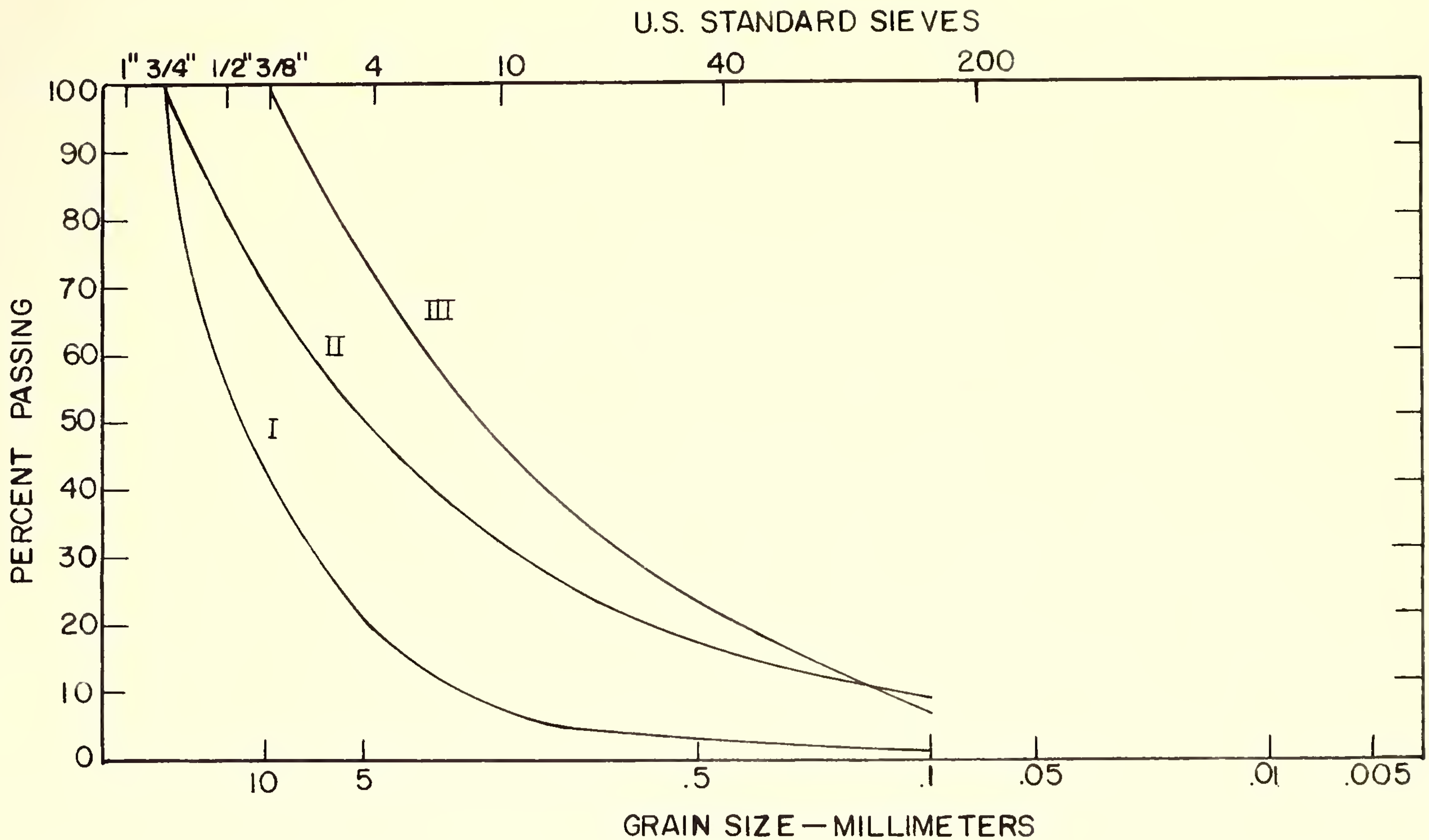

FIG. 3 GRAIN SIZE DISTRIBUTION CURVES OF MATERIAL GROUP II

TABLE 1

PHYSICAL DATA OF MATERIALS STUDIED

Material	Max. Std. AASHO Dry Density pcf	Optimum Moisture Content %	Plasticity Index	Specific Gravity
Sand-Soil Mix	121.4	11.6	16	2.67
Sandy Gravel	132.8	9.2	NP	2.65
Coarse Sand	113.7	14.5	NP	2.71
Quartzite *	130.7	7.2	NP	2.66
Limestone *	135.8	7.0	NP	2.75

* Note: Data apply to gradation III.

TABLE 2

QUANTITATIVE ANALYSIS OF MATERIAL GROUP II

Material	Fe_2O_3	Al_2O_3	SiO_2	CaO
Quartzite *	-	-	97.2%	-
Limestone *	-	-	12.1%	47.1%

* Note: Data apply to gradation III.

EQUIPMENT

Instruments

Two commercially available instruments were used during the testing program. Throughout the entire text, the instruments have been referred to as Instruments A and B.

Both instruments are portable type backscatter gages. Basically, a complete measuring unit has three distinctive component parts. They are the scaler, the density gage, and the moisture gage.

The radioactive source and a detection system are located in both the density and moisture gage. The function of the scaler is to transfer pulses transmitted from either surface gage into counts to be recorded on a series of glow tubes as the desired result.

Compaction and Measurement

For specimens obtained by a tamped compactive effort, a pneumatic compactor with a 4" diameter rubber tipped foot was used. Operating pressures for the compactor were between 60-80 psi. All samples were tested in a split steel mold. The dimensions of the mold used were 24" in diameter, 14½" in height, and ¼" thick. Bulk weights were determined on a portable floor scale using a lever-type balance. Accuracy of the scale was determined to be ± 0.5 of a pound.

PROCEDURES OF TESTING

General

All readings taken throughout the testing period were intended to be expressed as a count ratio with the instrument self-standards. However, during the course of the testing program, wide daily variations in self-standards were observed for Material Group I. This lead to an investigation relative to the validity of a count ratio analysis for Material Group I.*

An average reading was defined with the instrument oriented a minimum of three directions and with a minimum of two readings per direction. A minimum of six standard readings were used to define the average self-standard for a test. All readings were taken with the high voltage constant throughout the testing program. Concrete blocks were constructed and used periodically as an equivalent check to the instrument self-standard.

Soil preparation was usually completed by adding water, completely mixing the water and soil, and placing a cover over the soil overnight to prevent air drying. The following day, the soil was placed in the container

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* See page 56

and nuclear readings would commence. Moisture content samples were taken immediately after the test. Moisture contents were determined using standard oven drying procedures.

Material Group I

The materials tested in this group were a sand-soil mix, a coarse sand, and a sandy gravel. Variance in density was achieved primarily by adding varying amounts of water to each sample. In general, two densities, poured loose and tamped, were utilized in the placement for a given moisture content.

The materials were tested in the 24 inch split mold. The materials were built up in layers varying in thickness from 3/4" to 1½", the unit weight of the total sample being determined as each layer was placed. After the total layer height was determined to be greater than the depth of penetration for the instrument being tested, a count reading was obtained on each of the succeeding material layers. This resulted in testing of from one to four layers depending on the instrument and type of material under study.

Material Group II

The materials tested in this group were quartzite and limestone. Density variations were attributed to two methods of placement, poured loose and tamped, and the selection of 3 different gradations. Materials were crushed and hand selected to yield desired ranges of gradation.

For gradation I and II (see Figure 3) both methods of placement were applied to the soil completely dry. A third density condition was obtained by completely saturating the sample. Distilled water was used in the quartzite tests, gradation I and II, as an aid in investigating the effects upon density and moisture readings. Tap water was used for both the quartzite and limestone for gradation III.

Nuclear density count readings were taken under conditions of two different placement methods. The first method was to place the gage directly over the material and to make certain by visual observation that no immediate air gaps existed between the gage and material. The second procedure consisted of crushing a portion of the particular test material used, and placing it directly on the surface of the soil to act as a leveling course. The thickness of the leveling course used under the gage was visually made as thin as possible.

Nuclear moisture count readings were taken immediately after the density tests. Therefore, the moisture measurements, in essence, were obtained through the leveling course directly under the gage.

DISCUSSION OF RESULTS

Substrate Material Properties

Material Type

By far, the most important item of conjecture in the application of nuclear density gages to field use has been that of influence of material type upon density readings. A variety of opinions have been stated as to the relative effect of this parameter upon density determination.

Figures 4 and 5 show the results of density tests of Material Group I for the two instruments. These curves illustrate the data scattering for the three materials tested within this group although their validity may be questioned.* A single line of regression is shown for the combined test results. Results are expressed in a relative count procedure for the last layer tested.

Figures 6 and 7 are density results, plotted using the count ratio procedure, of Instrument A and Instrument B for Material Group II. The difference between calibration curves for the limestone and quartzite is quite obvious, with differences in densities for a given

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* See page 56

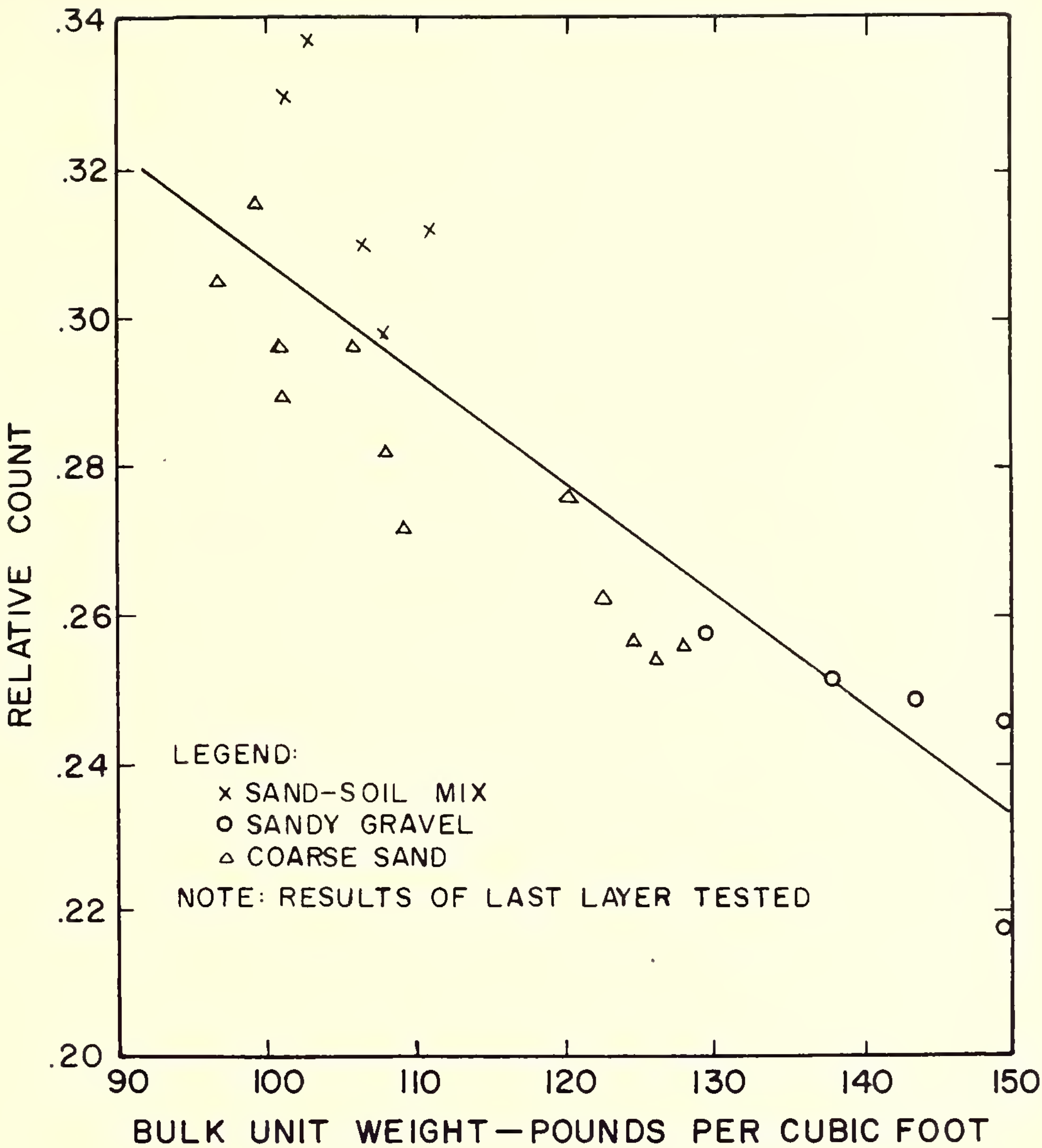

FIG. 4 DENSITY CALIBRATION CURVE FOR MATERIAL GROUP I-INSTRUMENT A

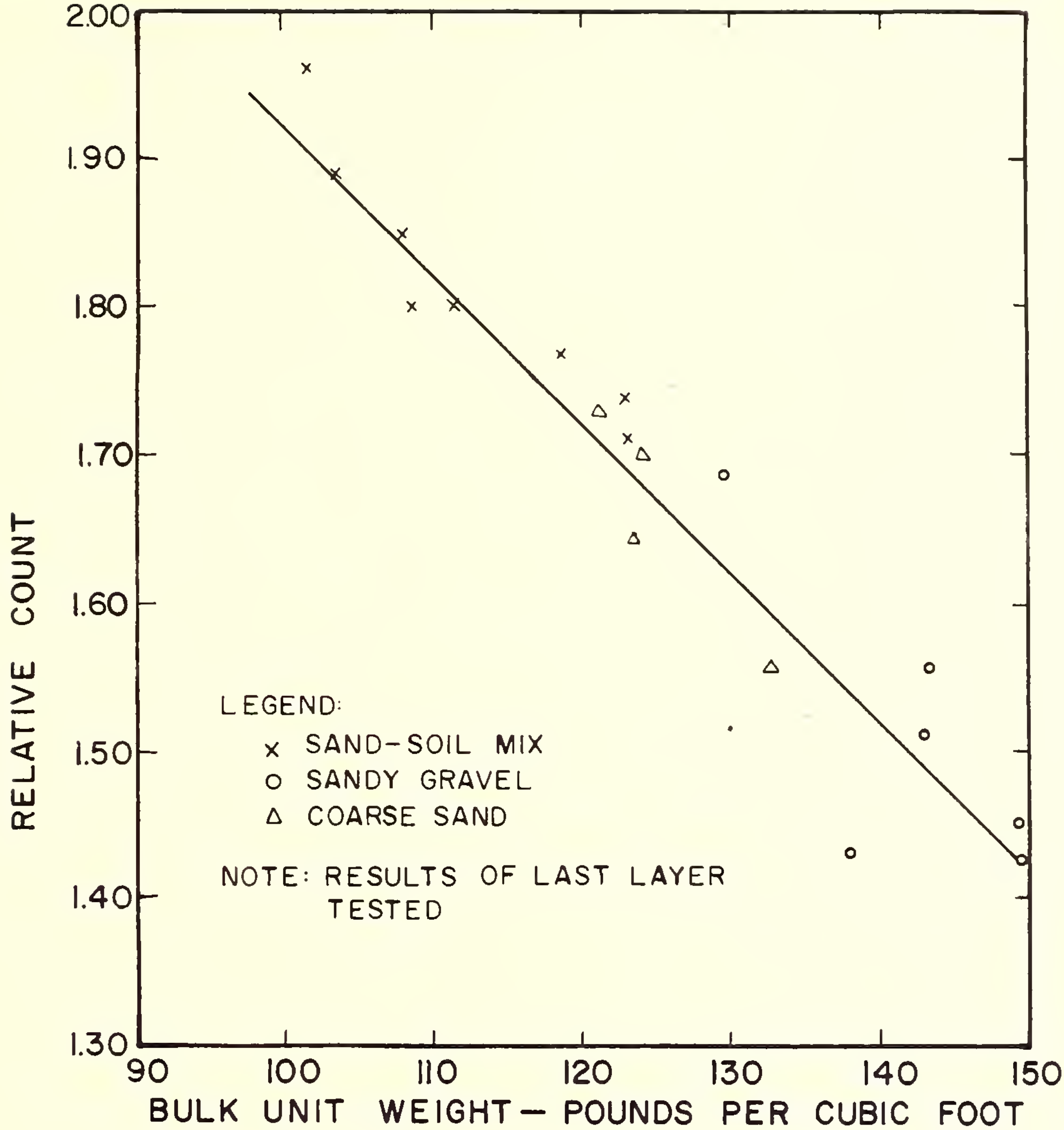

FIG. 5 DENSITY CALIBRATION CURVE FOR MATERIAL GROUP I - INSTRUMENT B

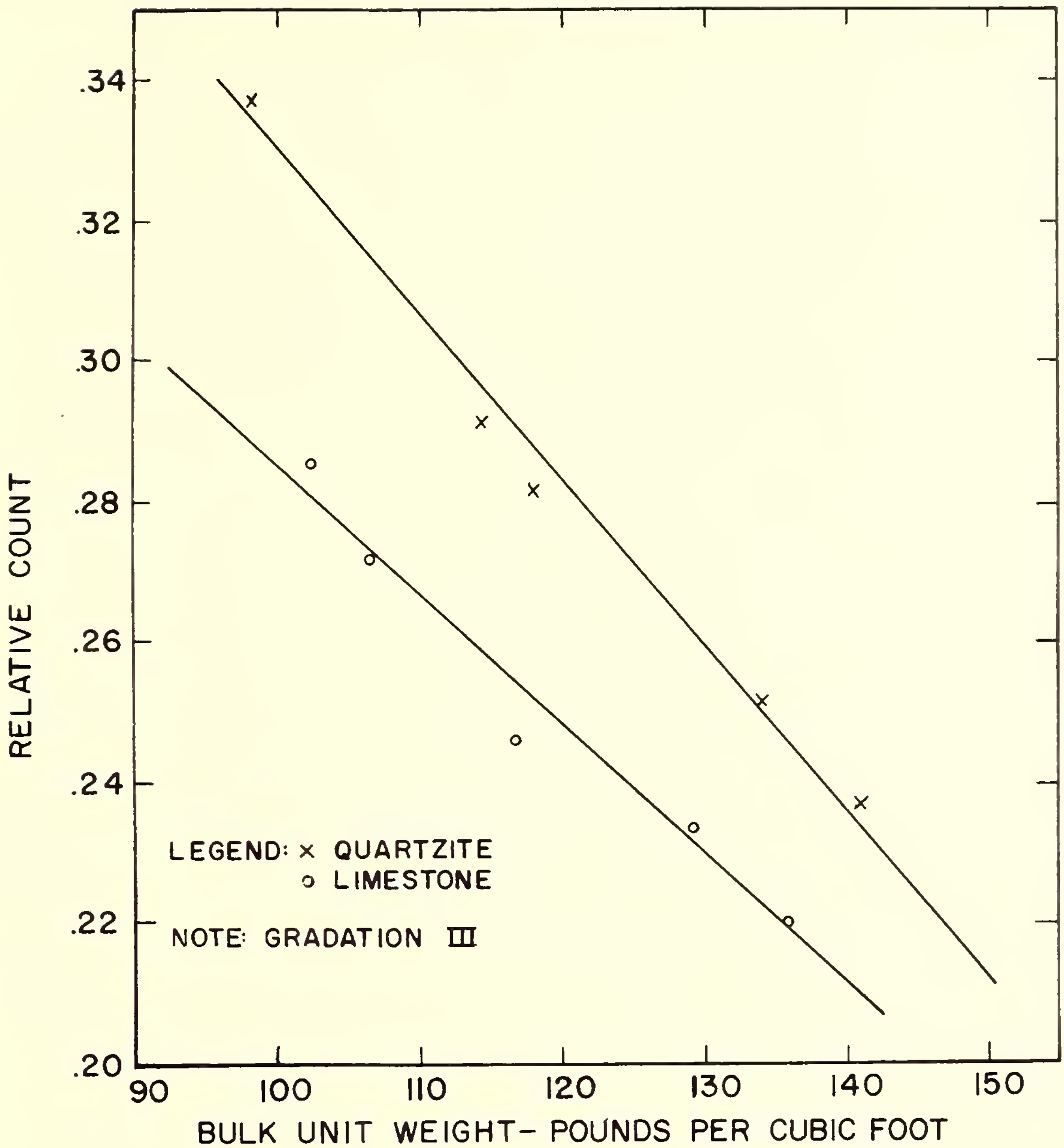

FIG. 6 DENSITY CALIBRATION CURVE FOR MATERIAL GROUP II - INSTRUMENT A

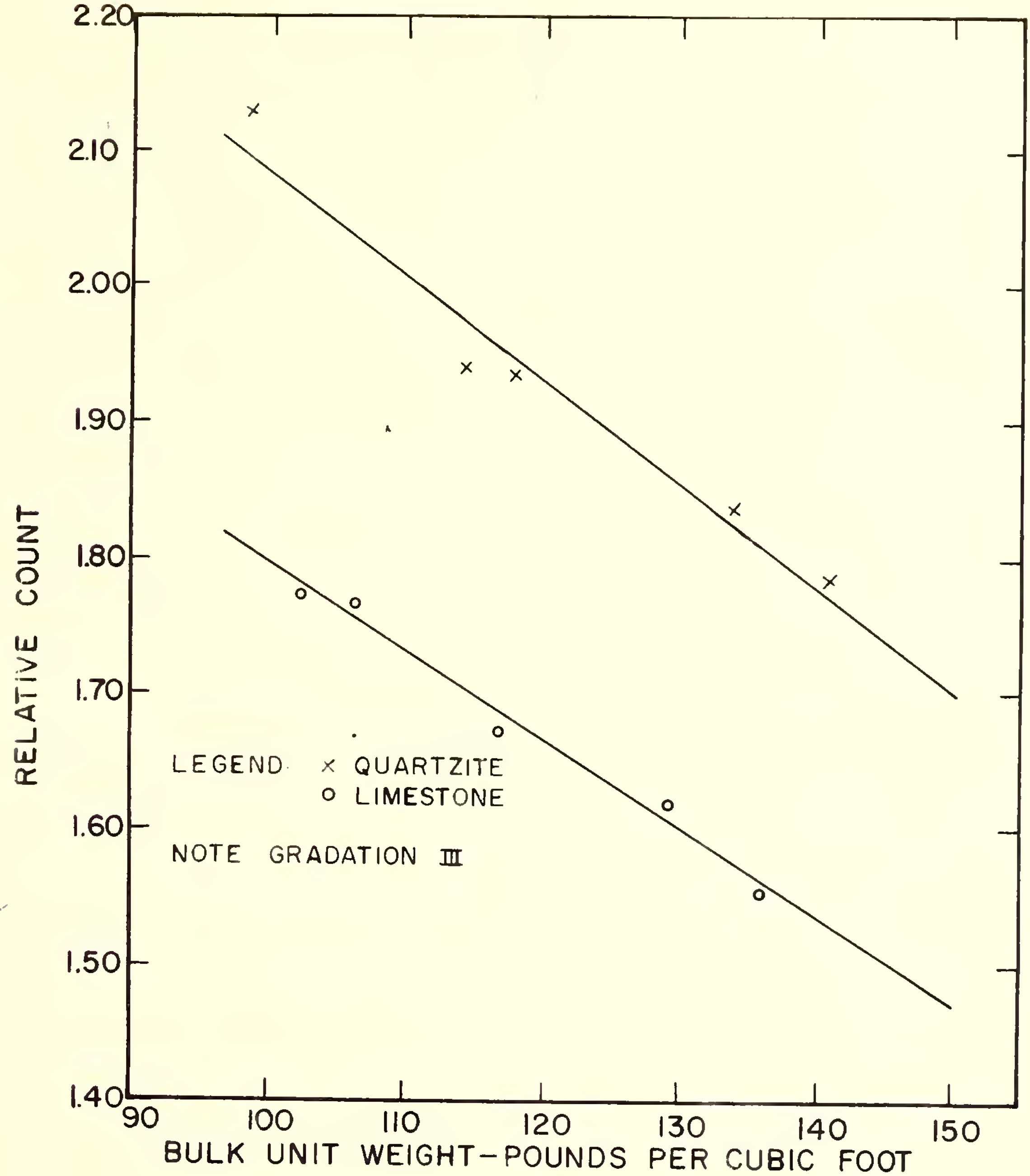

FIG. 7 DENSITY CALIBRATION CURVE FOR MATERIAL GROUP II-INSTRUMENT B

reading being approximately 15 pcf for Instrument A and approximately 35 pcf for Instrument B. It should be noted that both the limestone and quartzite shown have identical grain-size distribution curves (Gradation III).

The results show that the density count relationship is a function as the physical characteristics of the substrate. It has been stated in the section of this thesis dealing with the historical review that the general equation of the nuclear density unit is

$$I = I_o e^{-k_4 \gamma} (k_1 \gamma + k_2 \gamma^2 + k_3 \gamma^3).*$$

For the absorption effect $I_o e^{-k_4 \gamma}$ it is assumed that the mass absorption coefficient μ_m can be replaced by a design constant k_4, intrinsic to the circuitry of the unit. However, the mass absorption coefficient is hardly suitable for replacement by a design constant, as it is a function of both the photon energy and type of element. The values of the mass absorption coefficient and its dependence upon elements commonly found in soils has been given by Parsons and Lewis (9) and is shown in Figure 8. It can be seen from this graph that at energy levels lower than 0.3 Mev,**a significant departure among the mass absorption coefficients for various elements occurs.

RaBe has the major portion of its energy spectra at two energy levels. These levels are at 0.61 Mev and 0.35 Mev. Since a portion of the initial energy is lost due

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* See Page 6
** Mev - Million Electron Volts

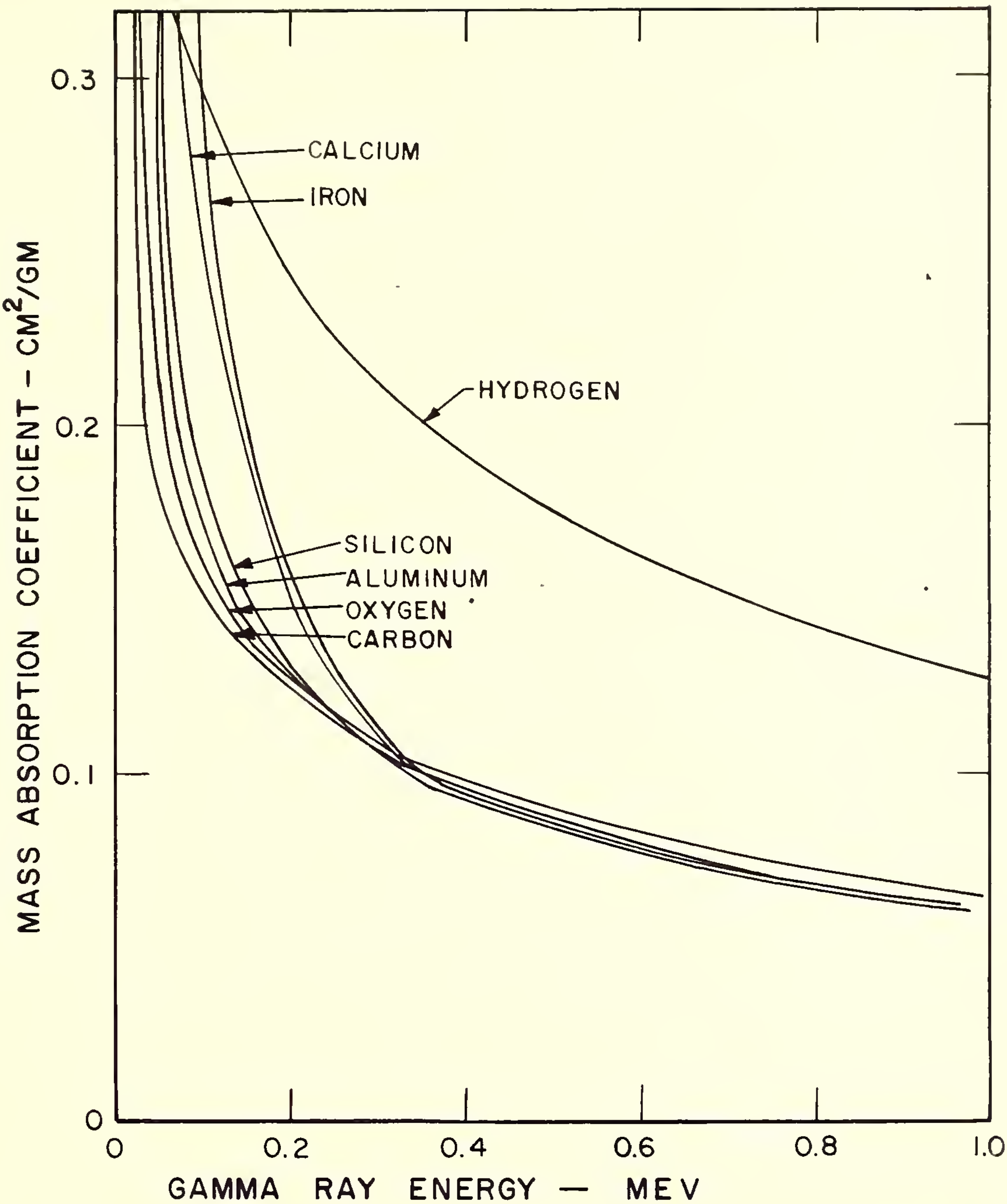

FIG. 8 RELATIONS BETWEEN MASS ABSORPTION COEFFICIENT AND THE ENERGY OF GAMMA RADIATION FOR ELEMENTS COMMONLY FOUND IN SOIL (FROM PARSONS AND LEWIS)

to the physical events that occur in the system and there also exists some radiation at energies of 0.18 Mev at the lower spectrum value, one must conclude that the possibility for radiation levels being found at or below the 0.3 Mev energy range is quite probable.

As a Cs^{137} radiation source has an energy level in which the initial level of the photon energy exists at 0.66 Mev, a subsequent smaller portion of photon energies may be expected to occur at the 0.3 Mev level. Hence, a smaller deviation can be expected to occur between soil types for a Cs^{137} source.

Table 2 shows the quantities of calcuim in the limestone and silicon in the quartzite. Referring to the discrepancy in mass absorption coefficients at 0.3 Mev between calcuim and silicon in Figure 8, it is possible to conceive that a large proportion of the deviation between the two materials shown in Figures 6 and 7 are due to the differing mass absorption coefficients.

One final point should be made concerning the relationship of mass absorption coefficients to changes in photon energy. Even at energy levels below 0.3 Mev it can be seen that for all the elements listed, with the exception of calcium, mass absorption coefficients vary slightly with gamma ray energies. This suggests the possibility that deviations of soil type for any combinations of these elements will definitely be smaller in contrast to calcareous type material. However, the evidence of a singular soil type deviation definitely hinders the adoption of present backscatter gages to wide field usage.

Figures 9 and 10 present moisture calibration curves for Instruments A and B. Material type had little effect in the results for both instruments. Therefore, a single line of regression was calculated for all soils. The effect of testing with distilled water was a slight decrease in counts when contrasted to results obtained by using ordinary tap water. Since just several tests were made with moisture greater than 15 pounds of water per cubic foot, conclusions regarding non linearity of the calibration curve cannot be stated.

As a rule, soil type has little effect upon moisture counts. Only when organic deposits are tested may deviations occur as the carbon and nitrogen usually found in these deposits exhibit a reduced neutron moderator characteristic similar to hydrogen.

Partridge and Rigden (10) have shown the effect of clay content on moisture measurements. (see Figure 11) It is well to remember that a moisture gage will measure all neutron moderation encompassed in the substrate system. As the clay content is increased in a soil containing water, an increased resistance to the bound water being driven out of the system by heat is encountered. Although a moisture unit will measure all forms of

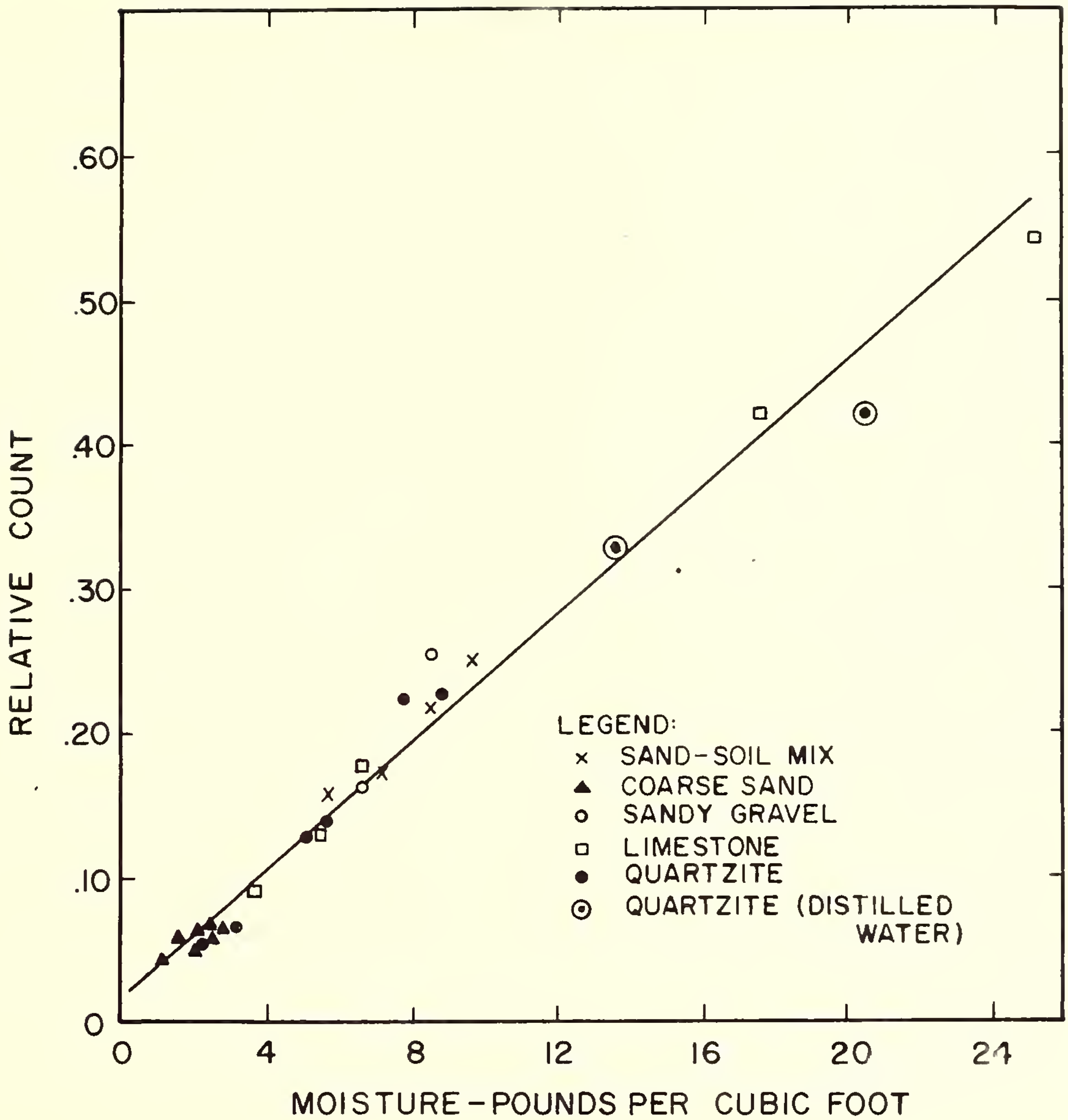

FIG. 9 MOISTURE CALIBRATION CURVE FOR MATERIAL GROUP I AND II – INSTRUMENT A

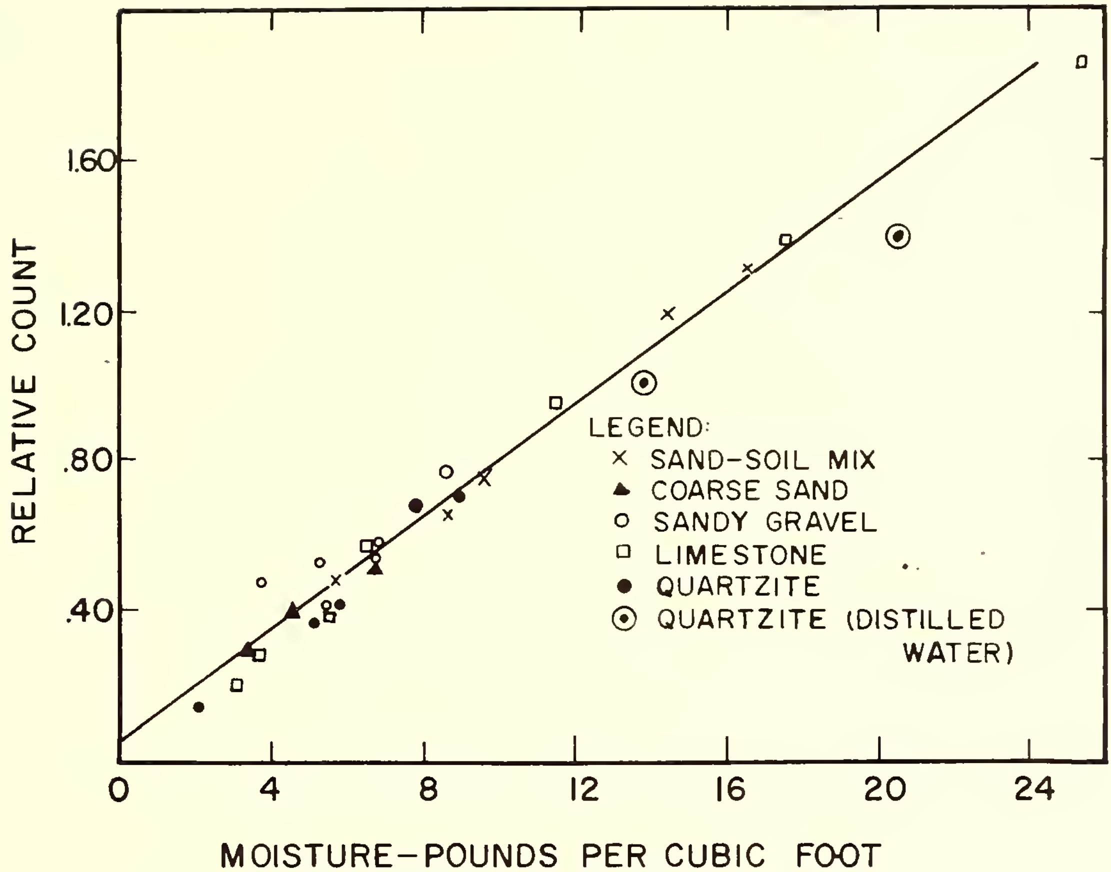

FIG. 10 MOISTURE CALIBRATION CURVE FOR MATERIAL GROUP I AND II – INSTRUMENT B

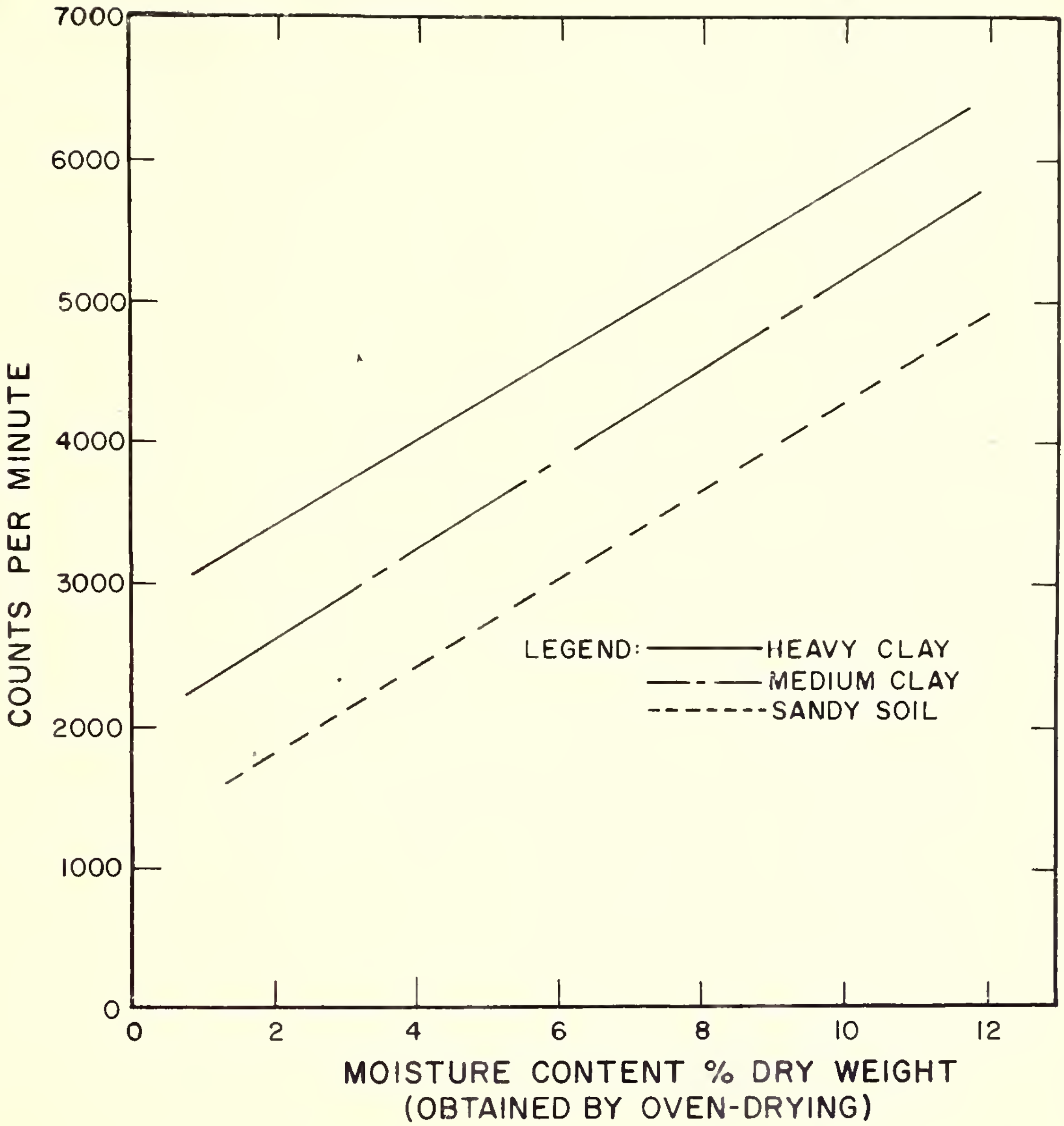

FIG. 11 EFFECT OF CLAY CONTENT ON MOISTURE MEASUREMENTS (FROM PARTDRIGE AND RIGDEN)

hydrogen present, conventional oven drying tests under standardized conditions do not effectively drive out all the water present. As a result, the nuclear method measures one quantity of water present while the conventional oven test measures a reduced quantity of water.

Grain Size Distribution

Reference has been made to the importance of mass absorption coefficients of various soil elements for nuclear density determination. However, the concept of this coefficient is a microphysical property assigned a macrophysical value. This lead the author to investigate the effect of testing an open graded material which in turn was crushed to a finer material. In essence, this became an analysis of whether similar mass absorption coefficients could be defined by the same soil element composition at different grain size distributions, which in turn, could possibily be indicative of the homogeneity of the substrate.

The results of the above tests are shown in Figures 12 and 13. Both instruments indicated similar count reductions for both materials tested as the open graded distribution was crushed finer. However, several points regarding the illustrations should be discussed.

It is not the feeling of the author that for every possible grain size distribution, at constant soil element composition, deviations between calibration curves can be

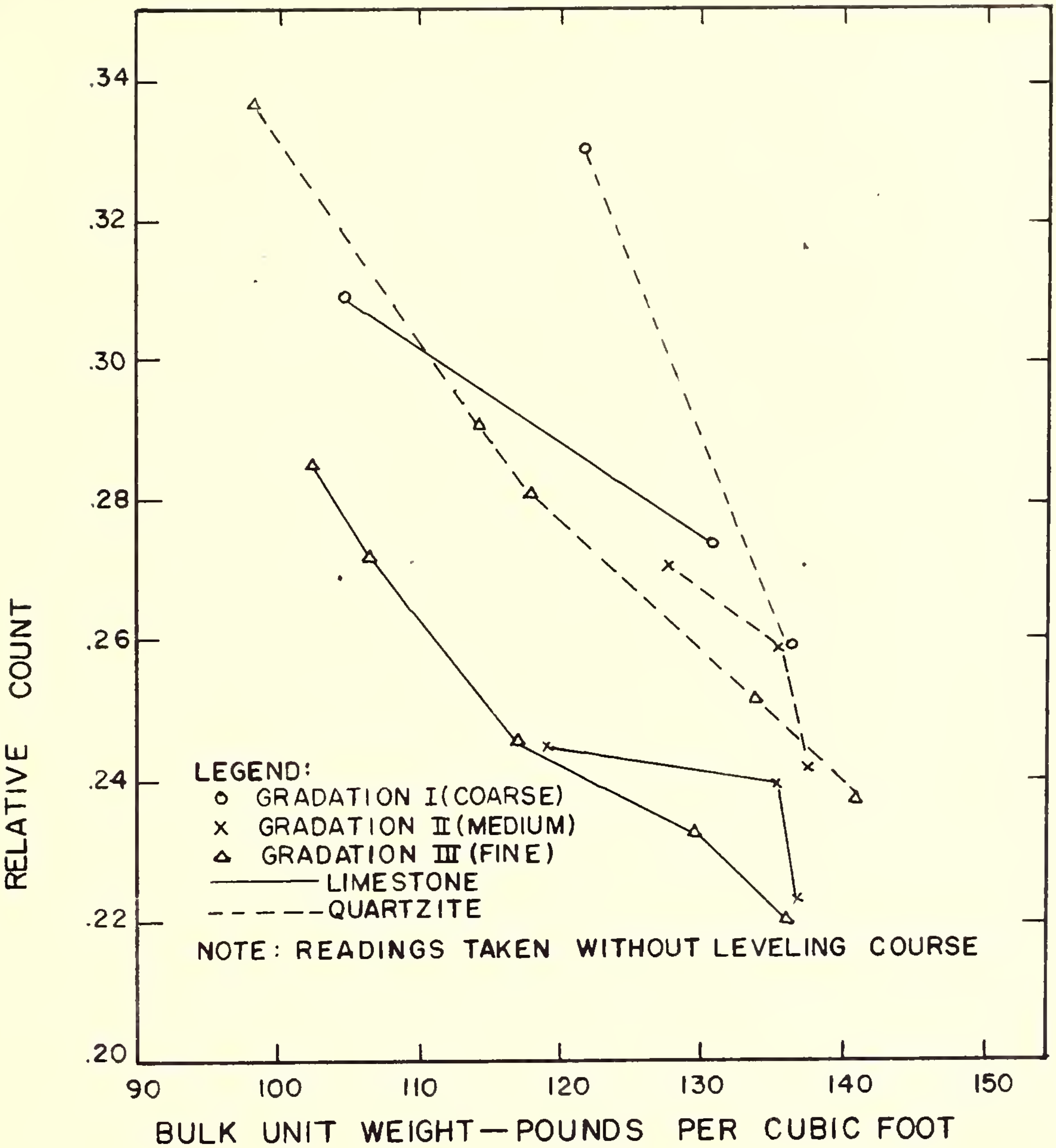

FIG. 12 EFFECT OF GRAIN SIZE DISTRIBUTION UPON DENSITY READINGS FOR MATERIAL GROUP II — INSTRUMENT A

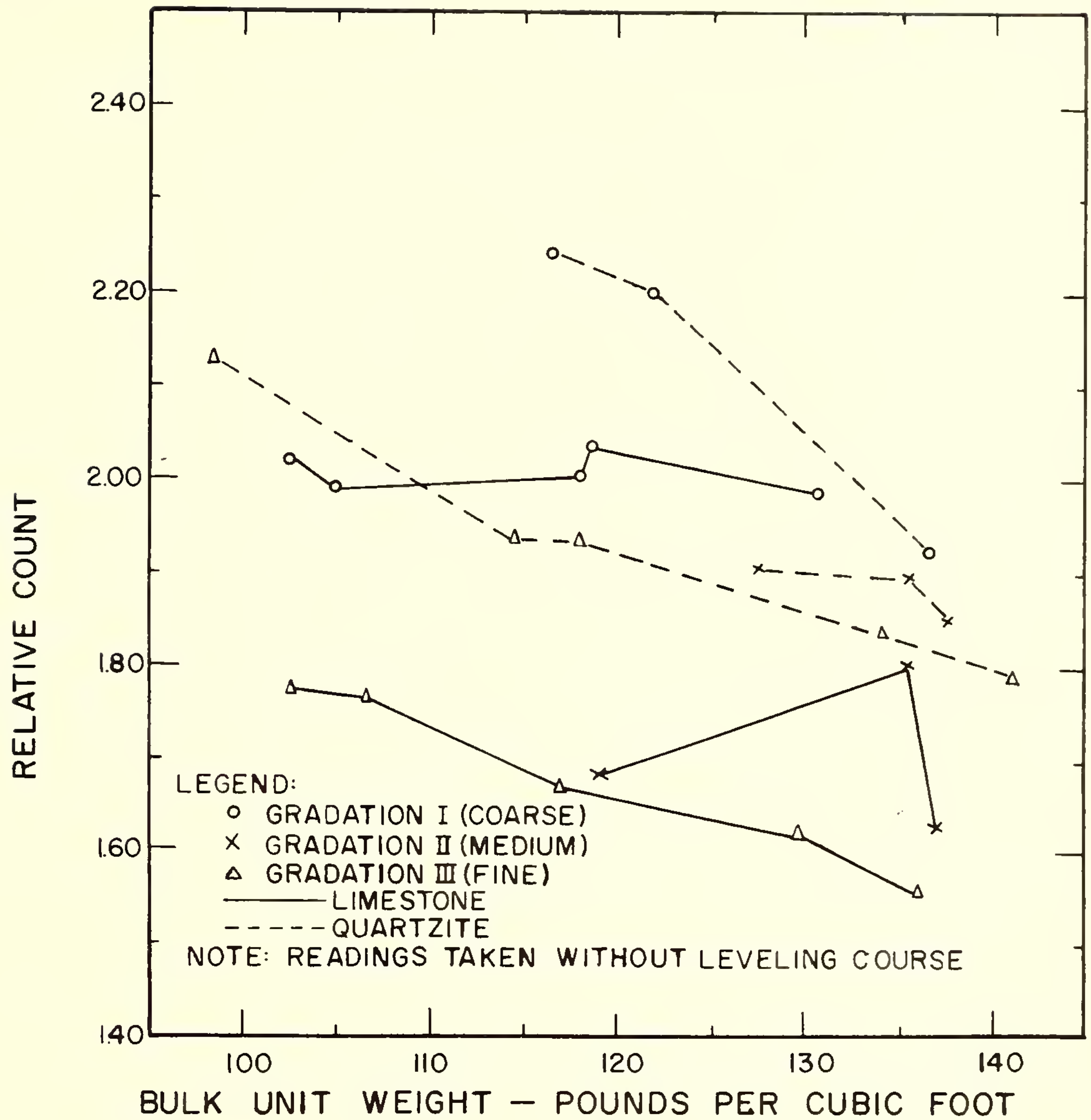

FIG. 13 EFFECT OF GRAIN SIZE DISTRIBUTION UPON DENSITY READINGS FOR MATERIAL GROUP II-INSTRUMENT B

expected to exist. Rather, it is felt that a certain state of grain size distribution this effect is negligible. To an extent, the data illustrate this feeling. In figures 12 and 13, a characteristic humped point is evident for all curves tested for Gradation II. It is believed that since this particular point was attained by compacting the specimen with the pneumatic tamper, there is a possibility that particle segregation may have occurred, thus leading to a subsequent smaller density of the top layer closest to the gage. Extreme points about the tamped point for the same gradation curve were tested on specimens carefully placed by use of a hand scoop. It is pointed out that for these extreme test points of Gradation II a relative proximity to the calibration curve for Gradation III does exist for all illustrations.

One might logically argue the fact that if particle segregation might be a possible cause of error for the tamped point of Gradation II, the large deviation of Gradation I from Gradation III might be a result of the identical error as it possesses a larger possibility of segregation during the placement. Against this argument, the relative positions of points obtained by hand placement for Gradation Curve I is pointed out. With the exception of the quartzite curve for Instrument A, these points are the initial low density results. The combination of their deviation from the other calibration curves and the reduced possibility of segregational effects contrasted to a point obtained with a pneumatic tamper, make the author believe that an effect of grain size distribution for a given soil type does exist and is dependent upon a physical phenomena rather than a procedure type error in placement of the soil in the mold.

Moisture in Material Mass

Hydrogen, like any other soil element, is respondent to gamma ray absorption. This effect is illustrated in Figure 8. Subsequently, data was analyzed for all materials to see if pronounced effects were noticeable.

Upon an analysis of data, no trends showing the effect of moisture on density counts were noticeable for either instrument. If existent, these deviations were confined in the scatter of data for a given material at the range of moisture contents obtained in testing.

Although hydrogen has the largest variation in mass absorption coefficient to other soil elements, its influence upon a density calibration curve can be expected to be insignificant due to the relative proportion of the weight of hydrogen to other soil elements. A report from the Road Research Laboratory (9) states:

> "It is estimated that the variation of calibration due to the hydrogen contained in water would not be more than 1-1½ pounds per cubic foot in bulk density for a variation in moisture content of 10 per cent."

Depth of Penetration

As radiation is emitted from a source in a backscatter gage, a limit of distance is imposed upon a radioactive particle which can penetrate the substrate, undergo the physical reactions of the system, and yet possess an energy range capable of being registered by the detection system of the nuclear unit in question.

For Instrument B, tests were made on Material Group I to determine the approximate depth to which the instruments measured density and moisture. Layers were built up in the mold and density and moisture counts were obtained as a function of the depth of material present in the mold.

The influence of depth of material upon the counts obtained using both gages is shown in Figures 14 and 15. From these graphs, the approximate depth of penetration for a given density or moisture value was defined as the lowest depth at which a consistent count reading was obtained regardless of material depth. Figure 16 represents the approximate depth of penetration curves for density and moisture content obtained with Instrument B.

For the results obtained with Instrument B, an average depth penetration of 8 inches occurred at 4 pounds of water per cubic foot contrasted to an average of 4½ inches at 20 pounds of water per cubic foot. For a density of 100 pounds per cubic foot, a depth of approximately

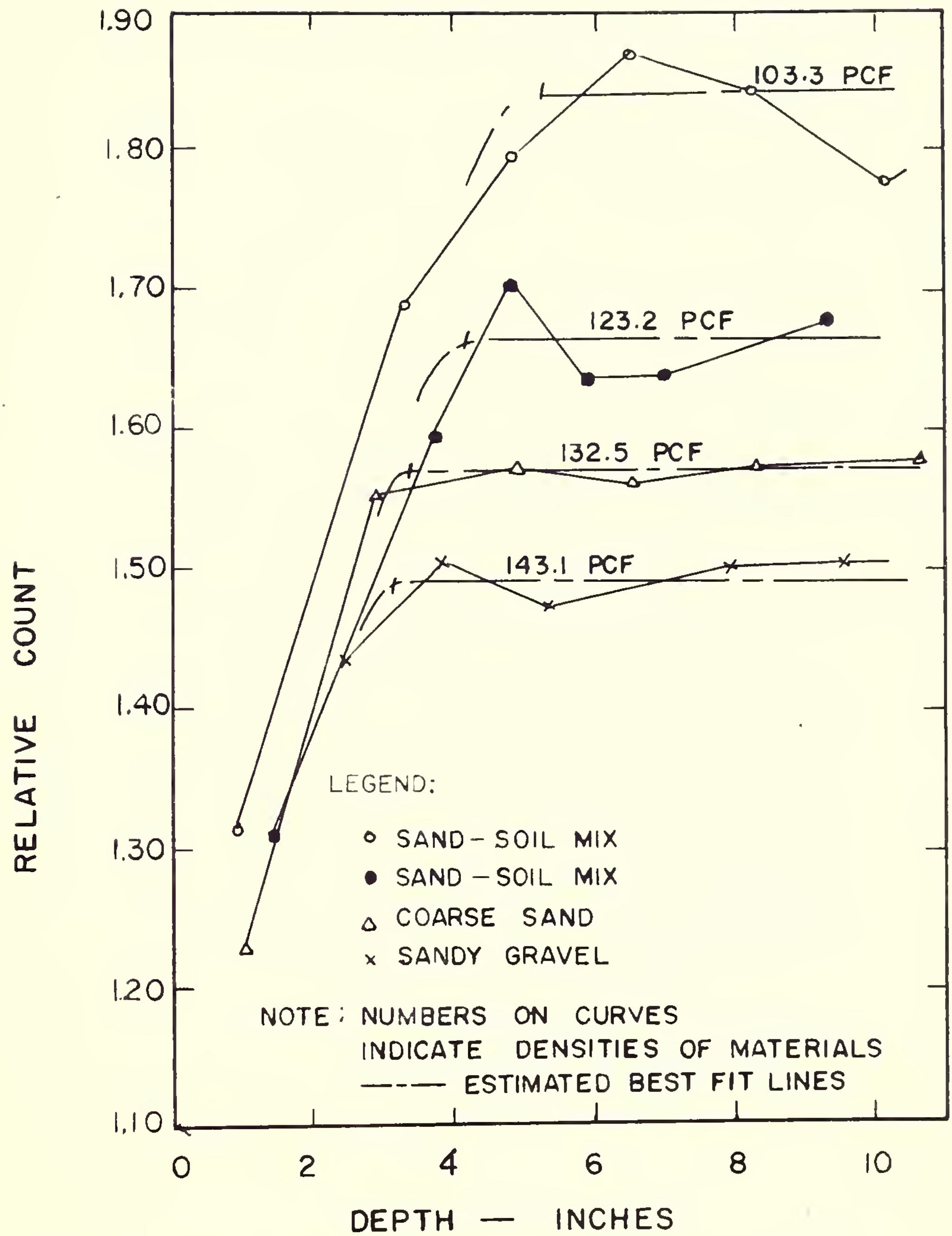

FIG. 14 INFLUENCE OF DEPTH OF MATERIAL ON RELATIVE COUNT FOR SEVERAL UNIT WEIGHTS — INSTRUMENT B

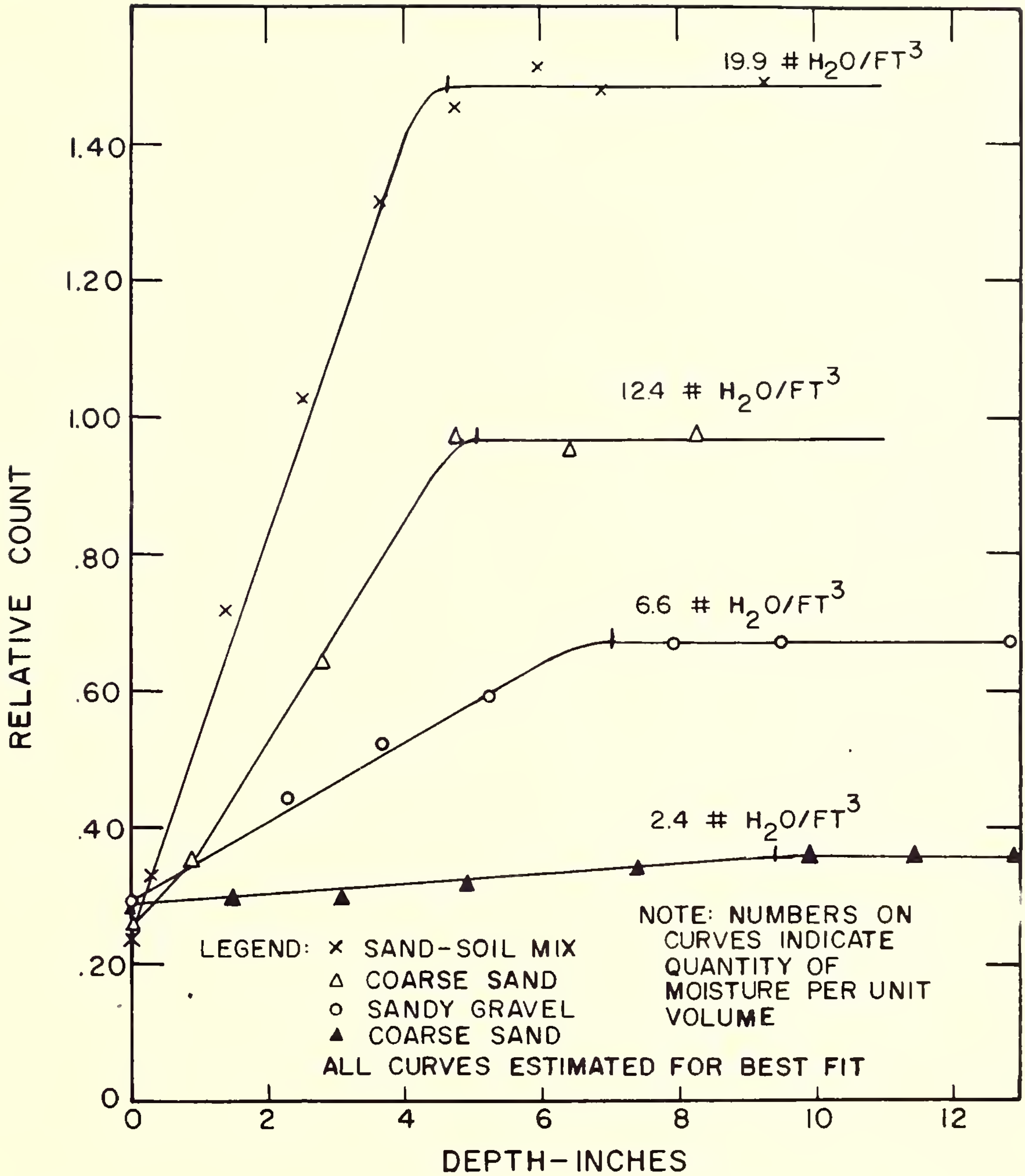

FIG. 15 INFLUENCE OF DEPTH OF MATERIAL ON RELATIVE COUNT FOR SEVERAL MOISTURE RANGES-INSTRUMENT B

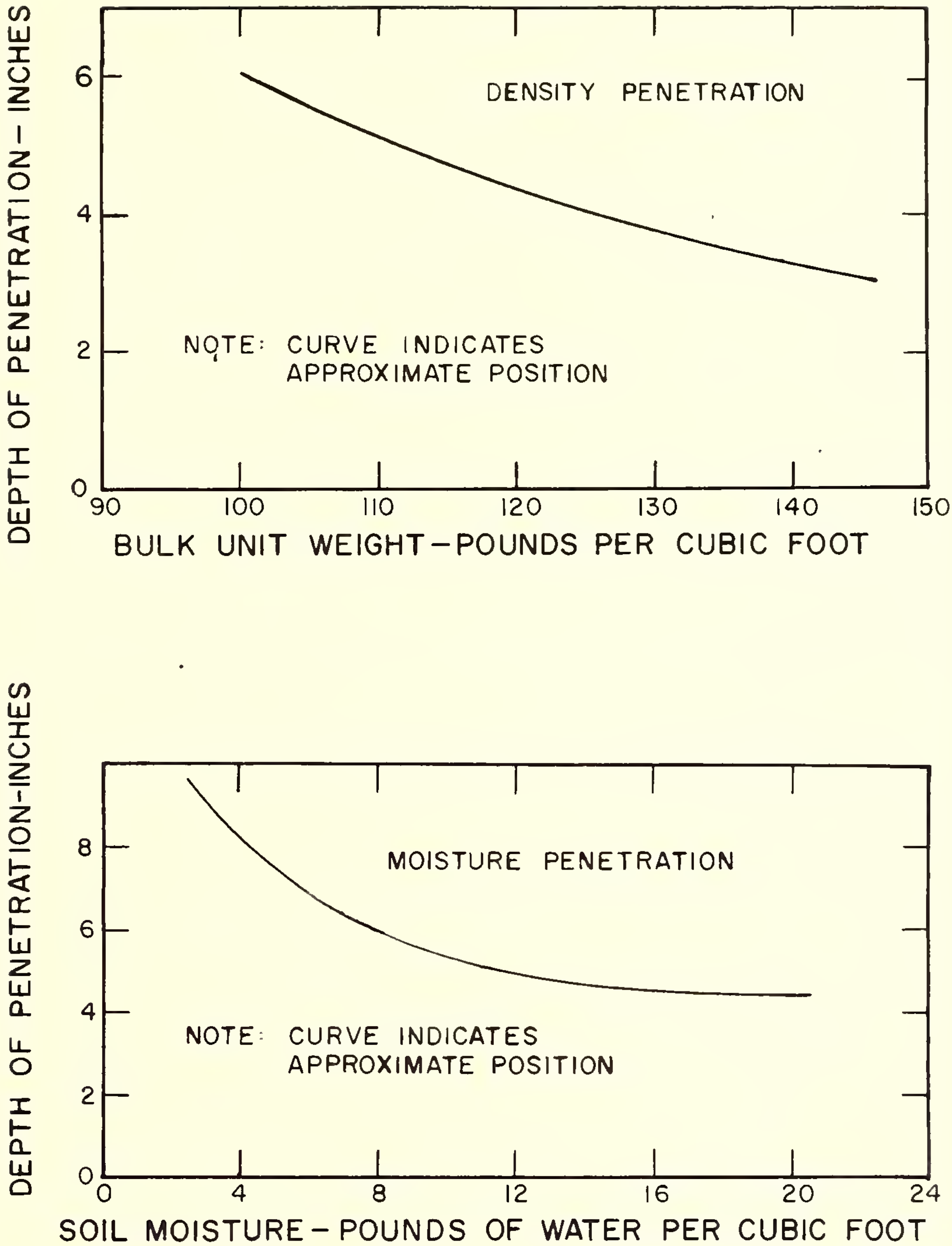

FIG. 16 APPROXIMATE DEPTH OF PENETRATION VERSUS BULK UNIT WEIGHT AND MOISTURE-INSTRUMENT B

5 inches is considered to be effective for the density gage while at about 150 pounds per cubic foot a depth of 3 inches results.

For Instrument A, the effective depth of penetration for the density gage was previously determined by Burgers(11). His results are based upon a study of heavy liquids and their employment as a self-standard check. This data is shown in Figure 17.

Figure 17 shows the influence of depth of liquid on density counts for several unit weights, whereas Figure 18 indicates the approximate depth of penetration for the density device. These results indicate a depth of penetration of approximately 6 inches at 100 pounds per cubic foot and 3½ inches at a density of 150 pounds per cubic foot.

Instrument Stability

Temperature

If a gage is to consistently perform its functional use, the effect of temperature upon its repeatability becomes an important matter. Tests were performed on both instruments at two temperature extremes, 0°F and 75°F. For the test performed at 0°F, instruments were placed in a cold room for a period of 2 hours before the tests were made. All readings were taken at constant high voltage and after an arbitrary warmup time of 15 minutes.

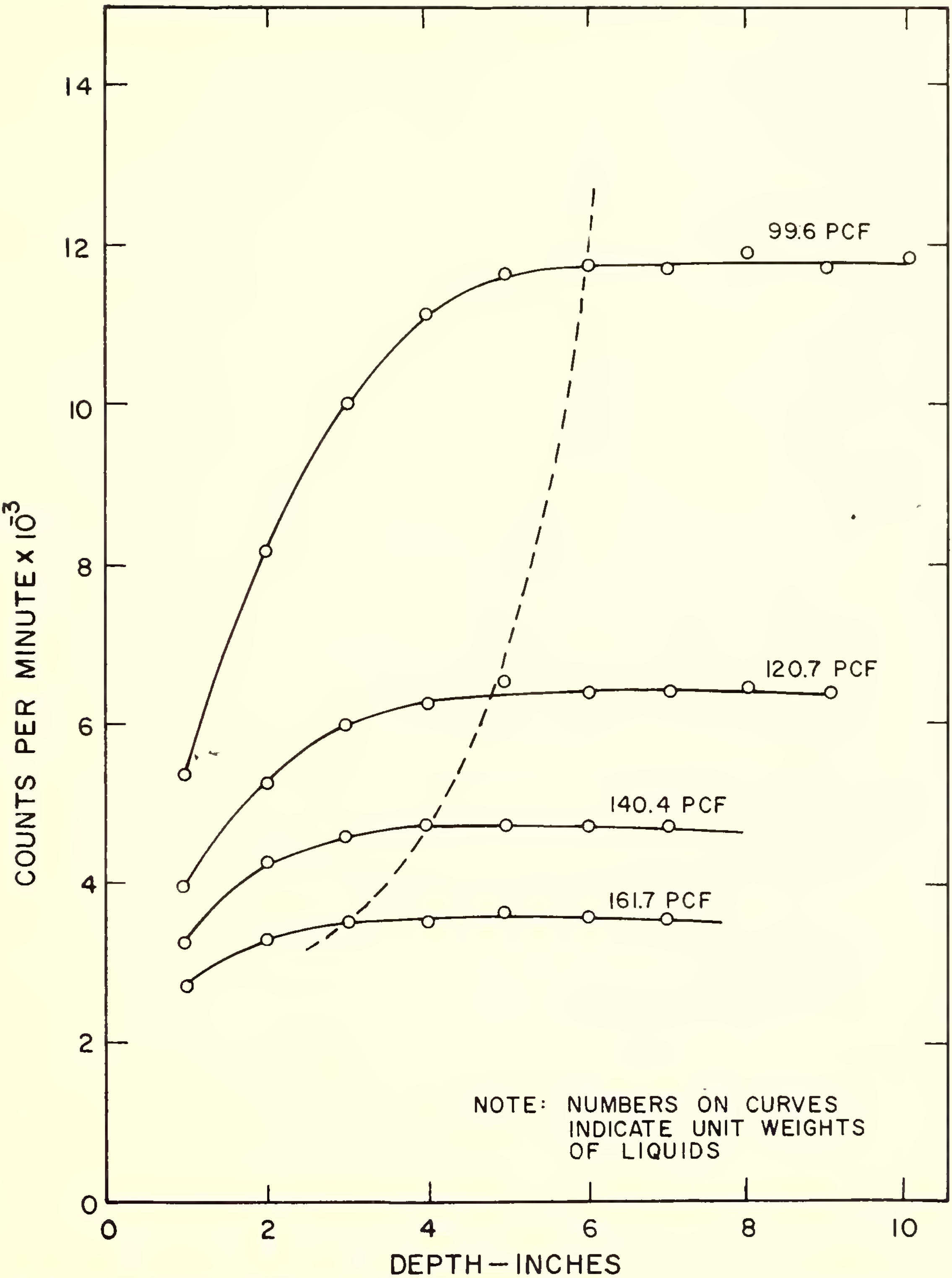

FIG. 17 INFLUENCE OF DEPTH OF LIQUID ON COUNTS PER MINUTE FOR SEVERAL UNIT WEIGHTS— INSTRUMENT A (FROM BURGERS)

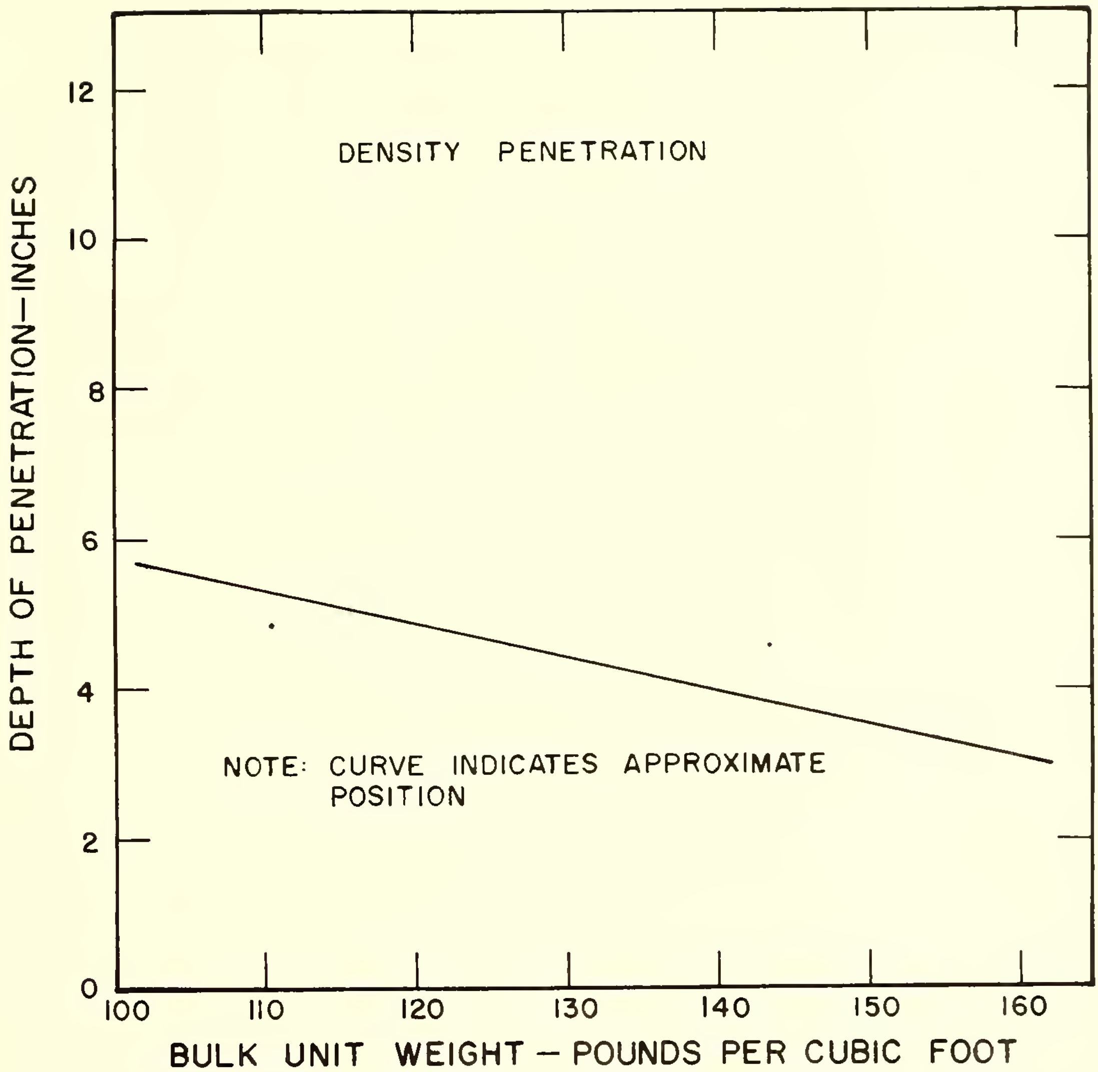

FIG. 18 APPROXIMATE DEPTH OF PENETRATION VERSUS BULK UNIT WEIGHT — INSTRUMENT A (INTERPOLATED FROM BURGERS)

The results of this test are shown in Table 3. For Instrument A density gage, a decrease of 357 counts at 0°F existed from the self-standard determined at 75°F. An increase of 244 counts was recorded for the moisture unit when subjected to the temperature of 0°F.

TABLE 3

EFFECT OF TEMPERATURE UPON COUNTS

Instrument A

Temperature	Density Gage Standard	Moisture Gage Standard
0°F	41665	19481
75°F	42022	19237

Instrument B

Temperature	Density Gage Standard	Moisture Gage Standard
0°F	Gage Inoperative	Gage Inoperative
75°F	19195	2240

Note: Both instruments placed in cold room 2 hours and "warmed up" for 15 minutes prior to testing at 0°F.

The reliable error for the density standard obtained at 75°F is 344, consequently a reliable lower limit for the reading can be established at 42678, just 13 counts above the reading obtained at 0°F. A reliable error for the moisture standard at 75°F gives an upper limit of 19469, in contrast to the reading of 19481 obtained at 0°F.

Therefore, due to the fact that for a temperature range of 75 F°, standard count variations were nearly confined to a reliable error for Instrument A; the effect of temperature upon count variation is considered negligible for this instrument.

When Instrument B was subjected to tests at 0°F, the gage became inoperative. First, the automatic timer mechanism failed to stop at a one minute interval and counts became continuous for several minutes. After stopping and starting the instrument again, only the first glow tube was operative. To avoid damage to the machine, tests were discontinued and the instrument was removed from the cold room.

Although definite conclusions for a defined count variation existing between the tested temperature range cannot be made for Instrument B, Parsons and Lewis (9) have shown that for a similar model of manufacturer B, density count variations can be considered negligible for temperatures ranging from 0°C to 40°C. For the moisture unit, count stability was more critical; as count increases were noted for temperatures below 7°C and a consequent count reduction for temperatures in excess of 30°C.

Timer

The ability of a timer to consistently and accurately measure a one minute interval is undoubtedly important.

However, it may be noted that if a count ratio procedure is adapted, consistency of the time interval rather than accuracy of measurement is of most importance since any deviation in time will be the same for both the self-standard and reading obtained. If the timer is inconsistent in measuring the time interval, both procedures, count per minute and a count ratio, will be in error.

Throughout the testing period, both instruments were periodically checked with a 0.1 second calibrated stopwatch. The results showed a high degree of accuracy and repeatability for a 1 minute time interval.

Voltage

Both instruments tested are equipped with an internal 6 volt battery for portable operation. As some deviation can be expected from the 6 volt supply throughout the use of the equipment, an investigation relative to the effect of voltage upon count readings was conducted. Voltage variation was achieved by use of a 50 watt, 25 ohm rheostat connected to a 12 volt external bettery with subsequent leads to the internal battery terminals.

Figure 19 is an illustration of the effect of battery voltage upon count readings for Instrument A. It can be seen for the density gage, that the change in self-standard was found to be 495 counts. However, the count ratio for readings taken on the concrete calibration block were practically constant at all voltage levels. The variation

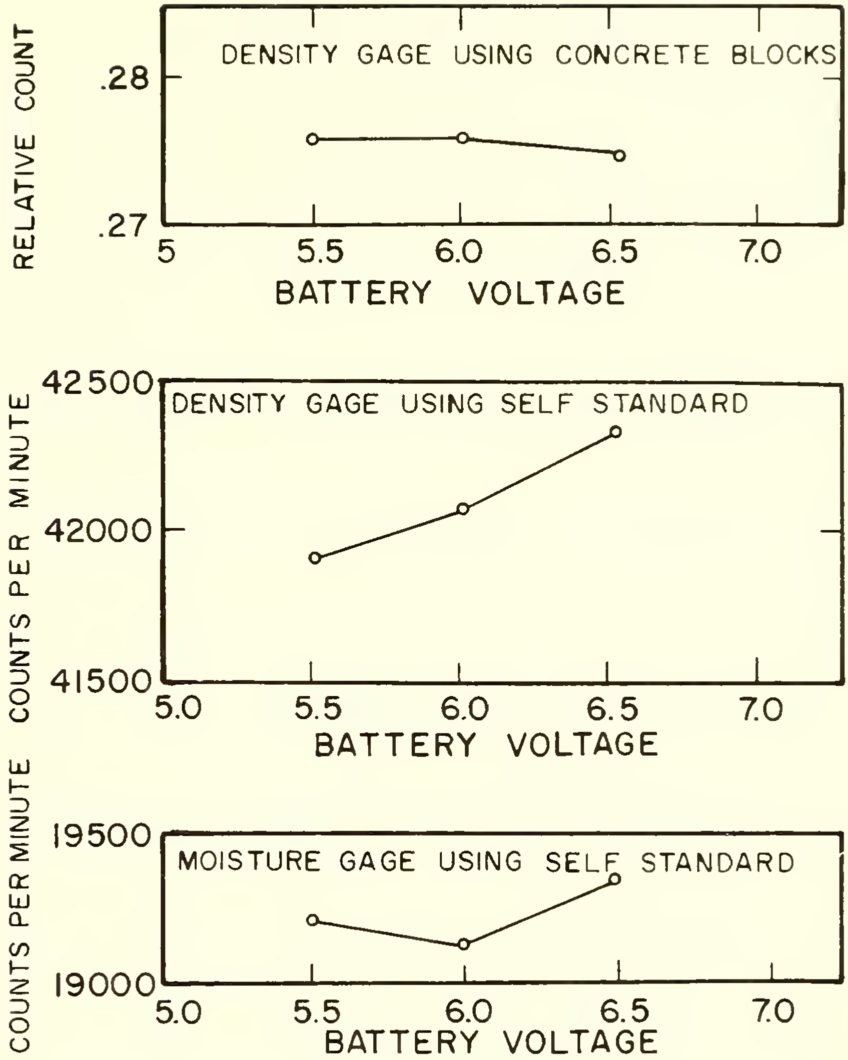

FIG. 19 EFFECT OF BATTERY VOLTAGE UPON COUNTS - INSTRUMENT A

of self-standard for the moisture unit was considered negligible. It should be noted however, that at 5.5 volts the moisture unit ceased functioning for the fourth count reading.

Data for Instrument B were not attainable due to an instrument malfunction, however, Parsons and Lewis (9) state in their discussion of a similar model that for the density gage,

> "the 'density' circuit registered reasonably consistent intensities of radiation.........between voltages 6.0 and 6.6"

For the moisture unit, they report;

> "The moisture circuit gave consistent results for voltages between 5.6 and 6.0"

Their conclusion as to the overall effect of both gages states:

> "Thus for consistent operation of the apparatus for both density and moisture content determination a supply voltage very close to 6 volts would be required."

During the research program, correspondence from the manufacturer advised that a more stringent control of supply voltage was necessary than initially indicated for the instrument. Consequently, control was exercised to ascertain that all readings were taken at or very close to 6 volts.

Aging

A high voltage, or plateau curve, is obtained by varying the high voltage on the scaler and taking count readings over the high voltage range. If the counts are then plotted as a function of the high voltage; a region, or plateau, will appear where only a slight increase in the counts will occur through a defined voltage range. The desirable operating voltage of the gage in question is then usually chosen as an intermediate voltage of the plateau voltage range.

Periodic high voltage plateau curves give an indication of the trend of count readings as a function of the time used. Also, by taking count readings on another standard system (a concrete block for example) a trend of the count ratio or relative count can be observed on the combined systems over a period of time.

Each density instrument used was assigned a seperate concrete block. On each block a permanent outline of the instruments was formed by glueing a piece of weathstripping onto the block. By placing the instrument within the outline and in the same orientation each time a reading was obtained, and variations in day to day tests due to different placement and direction were eliminated.

High Voltage curves for both instruments are shown in Figures 20, 21, and 22. Figures 20 and 22 only indicate the "plateau" region of the curves. It should be noted that the standard air gap was used to obtain only the final plateau curves for each instrument.* Also, for

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* See Page 56

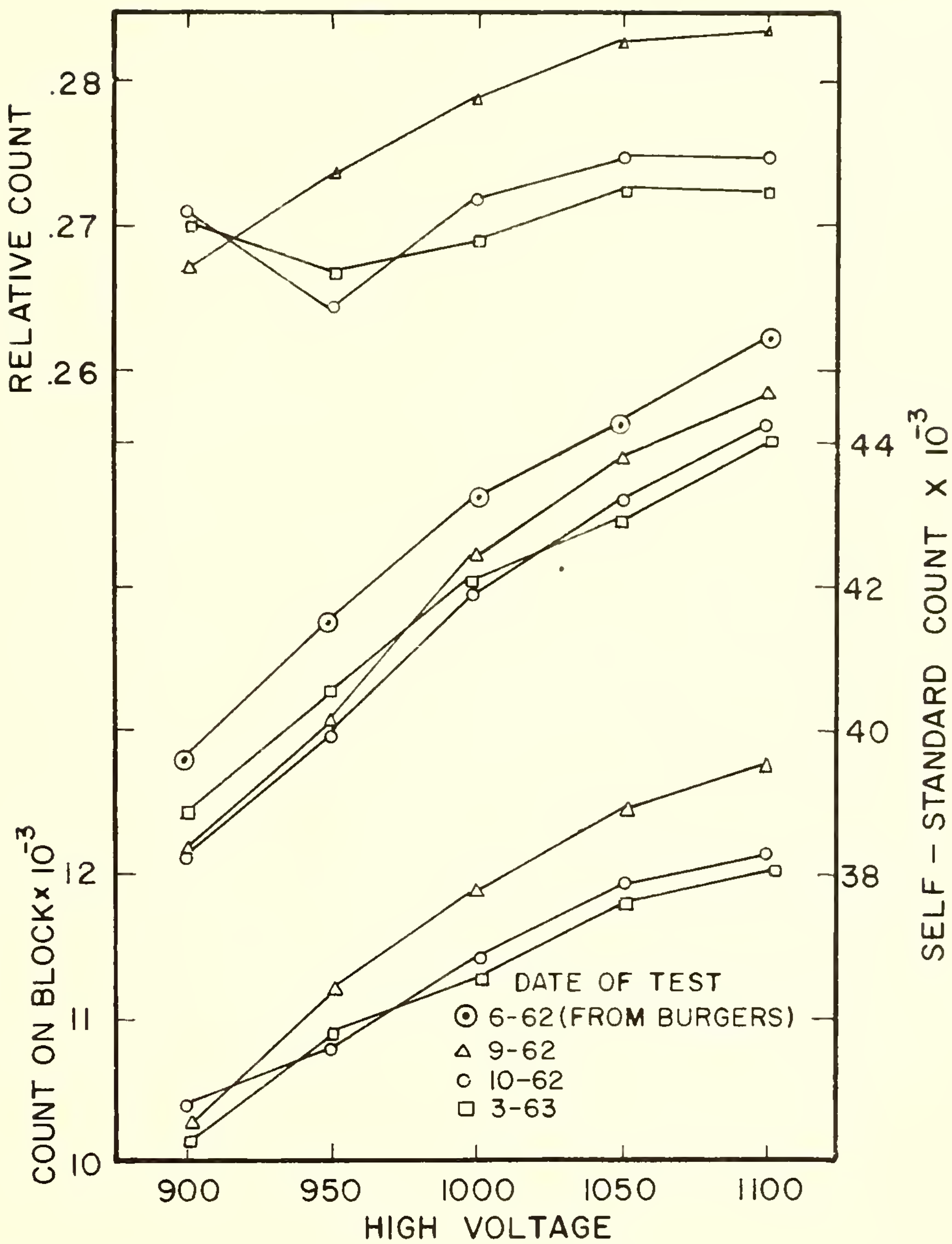

FIG. 20 HIGH VOLTAGE CURVES SHOWING COUNTS PER MINUTE ON CONCRETE BLOCK, SELF-STANDARD, AND COUNT RATIO OVER VARIABLE OPERATING VOLTAGES OF THE PLATEAU REGION-INSTRUMENT A

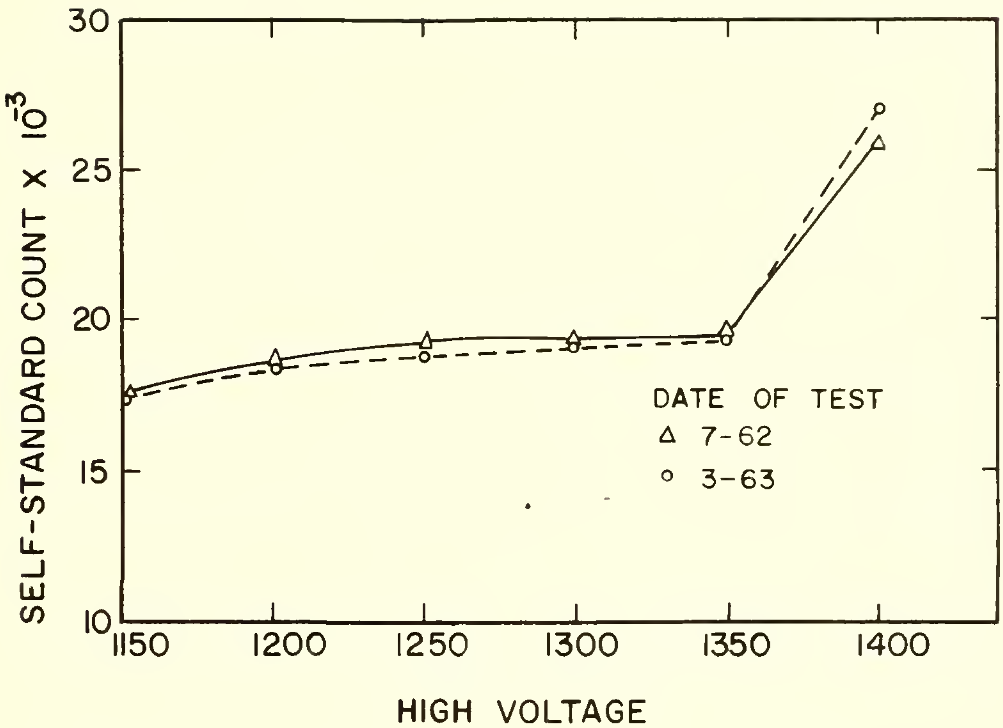

FIG.21 MOISTURE PLATEAU CURVES SHOWING SELF-STANDARD COUNTS PER MINUTE OVER VARIABLE OPERATING VOLTAGES—INSTRUMENT A

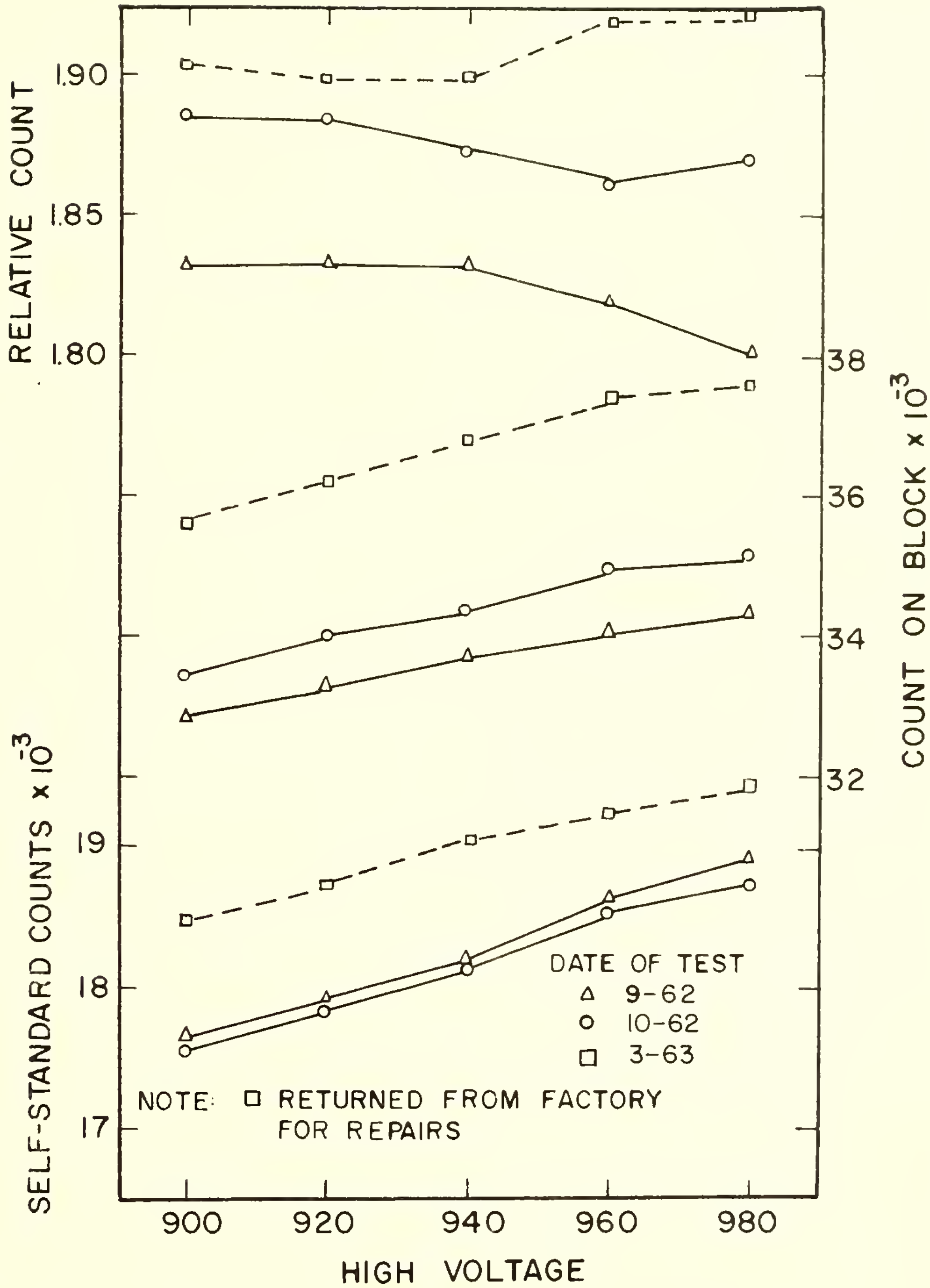

FIG. 22 HIGH VOLTAGE CURVES SHOWING COUNTS PER MINUTE ON CONCRETE BLOCK, SELF-STANDARD, AND COUNT RATIO OVER VARIABLE OPERATING VOLTAGES OF THE PLATEAU REGION-INSTRUMENT B

Instrument B, the plateau curve used with the standard air gap was obtained after the instrument was received from the factory where it was sent for repair of a faulty linkage system in the handle.

For the density gage of Instrument A, a large drop in the self-standard occurred immediately following the commencement of tests on Material Group I. This is illustrated in Figure 20 for the curves dated 6-62 and 9-62. Although the standard air gap was not used for these tests, it is believed that this large deviation cannot be attributed to the air gap due to the consistency of the ensuing day to day self-standards occurring below 43000 (See Figure 23). The reason for this occurrence was not explainable by the manufacturer. Consequently, since a possibility of permanent instrumentation malfunction may have occurred, a reservation as to the validity of the results of the sandy-gravel material may be necessary.

Although, validity of the self-standards and relative count results of the plateau curve may be questioned due to the non use of the air gap, a trend in count readings can be safely observed for the readings taken on the concrete block. They illustrate that, a count reduction of a system tested can be expected to occur over a period of time. In general, the use of a count ratio procedure will eliminate any variation due to age effects of the counter tubes. However, Pocock (6) has shown mathematically that the use of a count ratio procedure will not eliminate any variations due to source deterioration. This fact suggests that periodic recalibration of the instrument is necessary regardless of which method of analysis, count ratio or direct counts per minute, is used. This recalibration is very important for instruments employing C_s^{137} source since the half-life of C_s^{137} is 33 years, in contrast to the 1620 year half-life of Ra-Be. Since a count ratio procedure was adopted, and the entire testing program was completed in 6 months, the effect of aging was considered to be negligible.

For the moisture gage of Instrument A, the obvious stability of the gage is evident over the entire testing program. Although the standard air gap was not used for the initial curve, its effect upon the moisture self-standard is pointed out on page 60 as being negligible. The reader is referred to page 60 for a further discussion of this occurrence.

Even though the counts obtained on the concrete block show an increase for Instrument B for the curves dated 9-62 and 10-62; the relative small time interval, the type source used, and the fact that the two curves are very slightly in excess of the reliable error limits compel the author to feel that this increase is not attributable to any aging effect of the instrument.

The fact that a different plateau curve was obtained on Instrument B after the instrument was returned from the factory for repairs, points out that new calibration curves should be obtained each time a serious instrument defect warrants shipment to the manufacturer for repairs.

Instrument Test Procedure

Reliance of Self-Standard

The accuracy and repeatability of the instrument self-standard reading for daily use is of extreme importance. The purpose of this reading is to give the user an immediate check on the overall stability of the gage and it serves as a reference count for the count ratio. Self-standard readings are usually taken on standard blocks (concrete for example) or the instrument itself may have an internal standard.

Self-standard readings, for both density and moisture, were taken for each test performed throughout the entire testing program. For the Material Group I tests, extreme variances in the self-standard were noticed between daily tests. As self-standard readings were taken with the gage placed on the laboratory floor, a wooden stand, 12" in height, was constructed to permit an air gap to exist between the floor and bottom of the measuring device. This stand (referred to hereafter as the standard air gap) was used for all tests in Material Group II. A plot of the standard readings versus test number is shown in figures 23 and 24.

It can be seen that the Material Group I tests had a larger variation in self-standards than for the tests of Material Group II. Although it might be logically deduced that the reduction of the self-standards was attributable to the standard air gap, there is a possibility that instrument malfunction may have influenced these readings.

It has already been stated for Instrument A that a question as to the validity of the initial density results due to instrument stability exists. For Instrument B, the gage was sent to the manufacturer after a discussion pertaining to the self-standard.variation. It was suggested that a linkage which is used to raise and lower the radioactive source in the gage was faulty. However, latter correspondence from the manufacturer was received acknowledging the effect of an air gap in reducing self-standard variations.

Unfortunately, the existance of these two possibilities leads to conflicting methods of results analysis. If it is due to the standard air gap, then it could be concluded that a count ratio analysis would be invalid due to the uncertainty of the standard determined as the reference count. However, if an instrument effect reflecting the electronic stability is assumed, a count ratio analysis would tend to reduce the data scattering about a line of

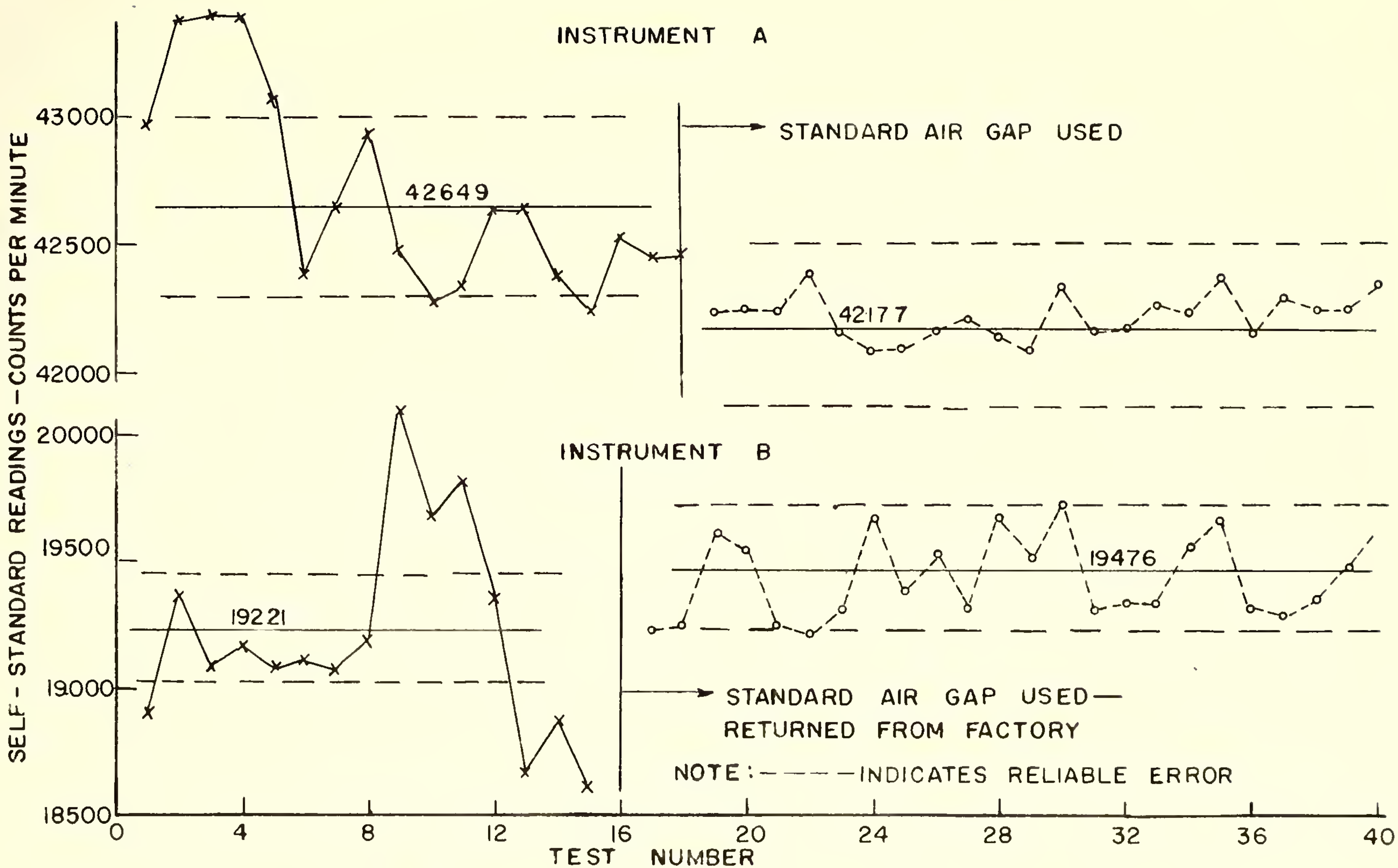

FIG. 23 EFFECT OF STANDARD AIR GAP UNDER DENSITY GAGE UPON SELF-STANDARD READINGS

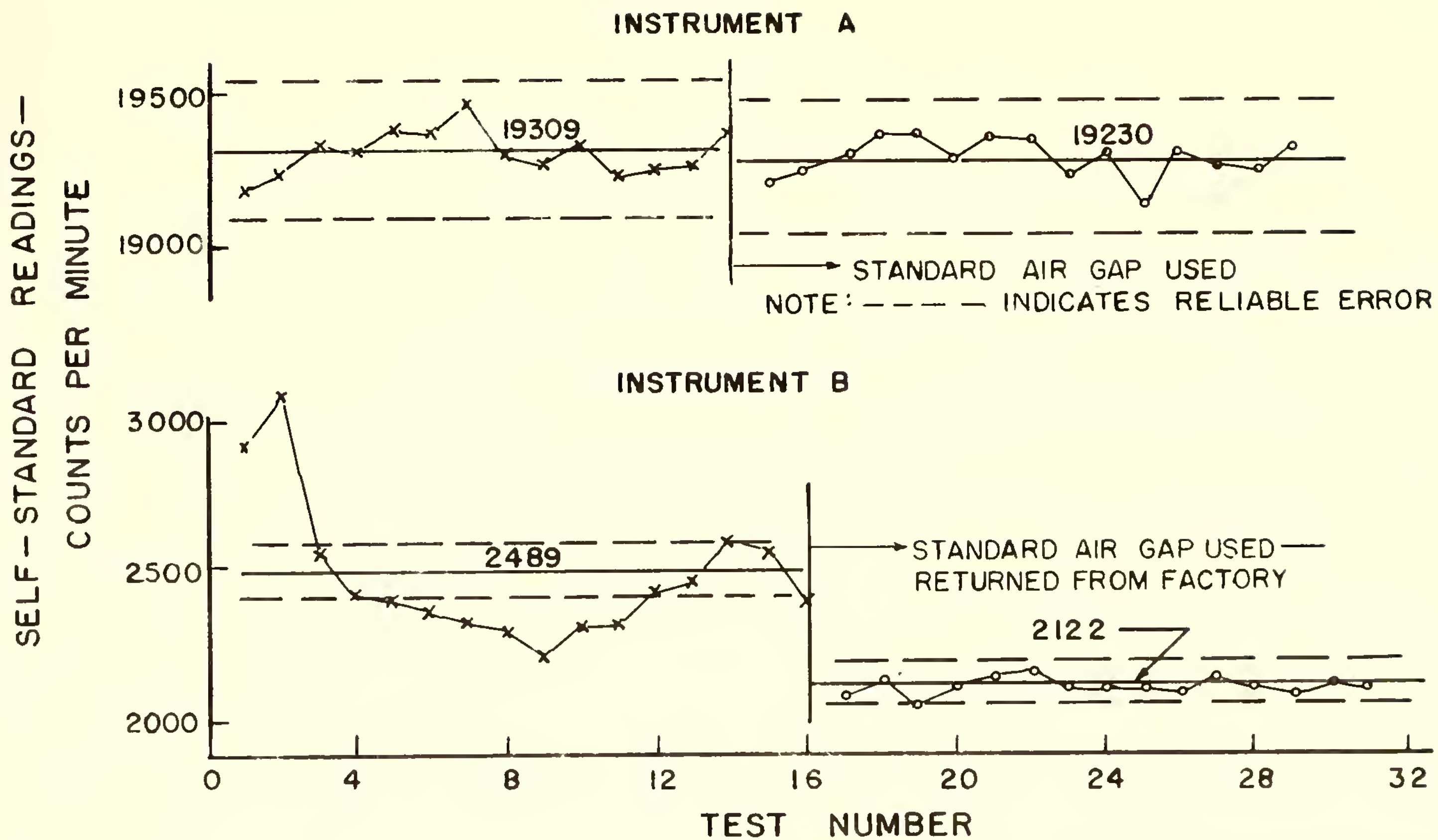

FIG. 24 EFFECT OF STANDARD AIR GAP UNDER MOISTURE GAGE UPON SELF-STANDARD READINGS

regression for the calibration.

Consequently, the data were analyzed for both methods of expressing results. This analysis is shown in Figures 25, 26, and 27. It was found that it was not necessary to show the difference in results for the moisture gage of Instrument A; due to the consistency of the self-standards throughout the entire testing program. It should be noted that this particular gage has an air gap built into its standard block.

In figure 27, it is obvious that the use of a relative count procedure reduced the data scattering from results obtained with a count per minute analysis for the moisture gage of Instrument B.

In general, the moisture gage self-standards would be expected to have a small proportion of the variation attributable to interference with the substrate system upon which the gage is placed. The reason for this being that the system for density readings is dependent upon mass; while moisture methods utilize fast neutron moderators. Since the concrete floor on which the gages where placed to determine the self-standards for Material Group I tests can be classified as a mass system moreso than a moderating system, it follows that the floor would be expected to interfere more with a density backscatter device than with a moisture unit.

A count ratio procedure was chosen for use in plotting

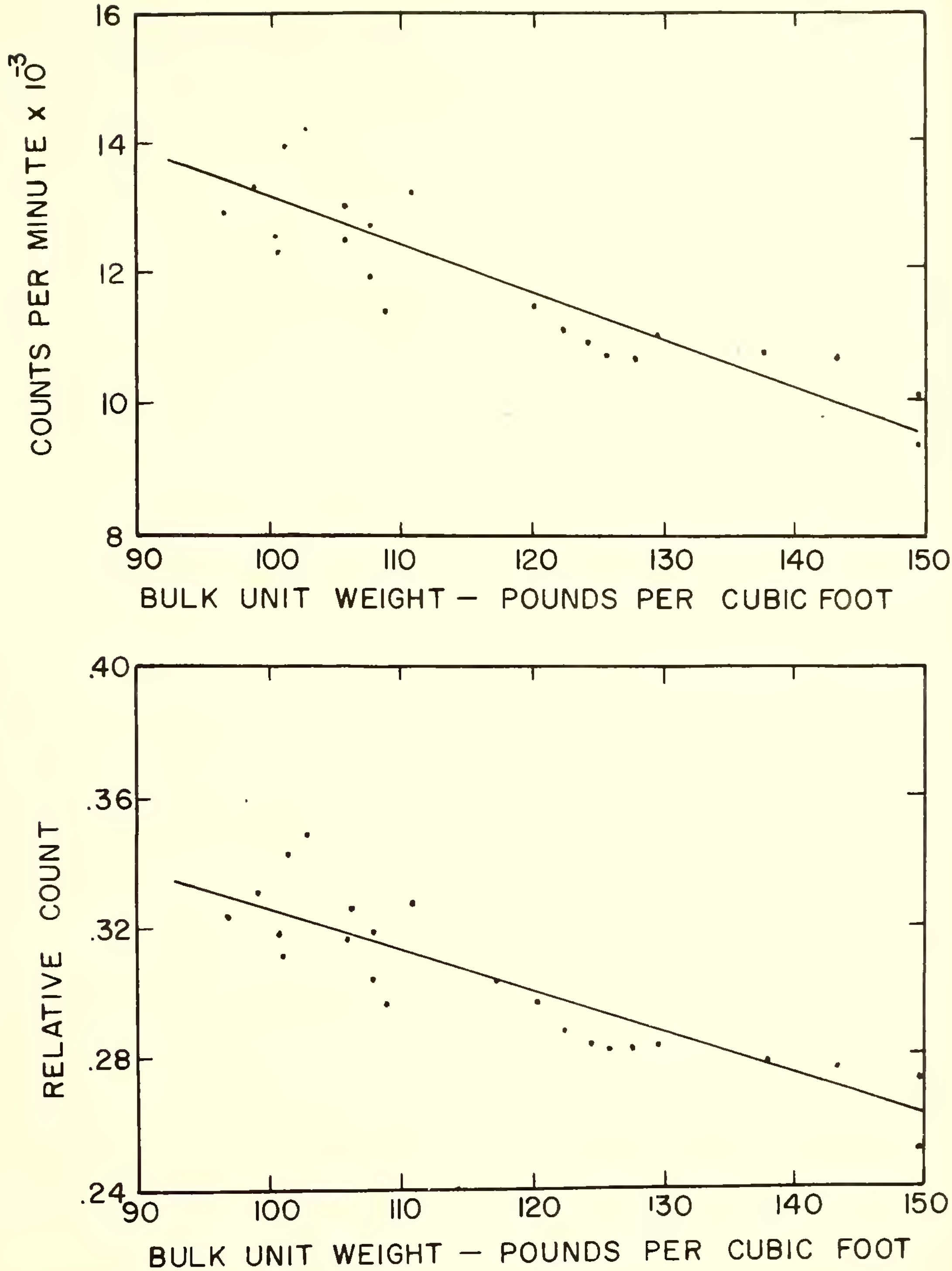

FIG. 25 DENSITY CALIBRATION RESULTS EXPRESSED AS COUNTS PER MINUTE AND RELATIVE COUNT FOR MATERIAL GROUP I — INSTRUMENT A

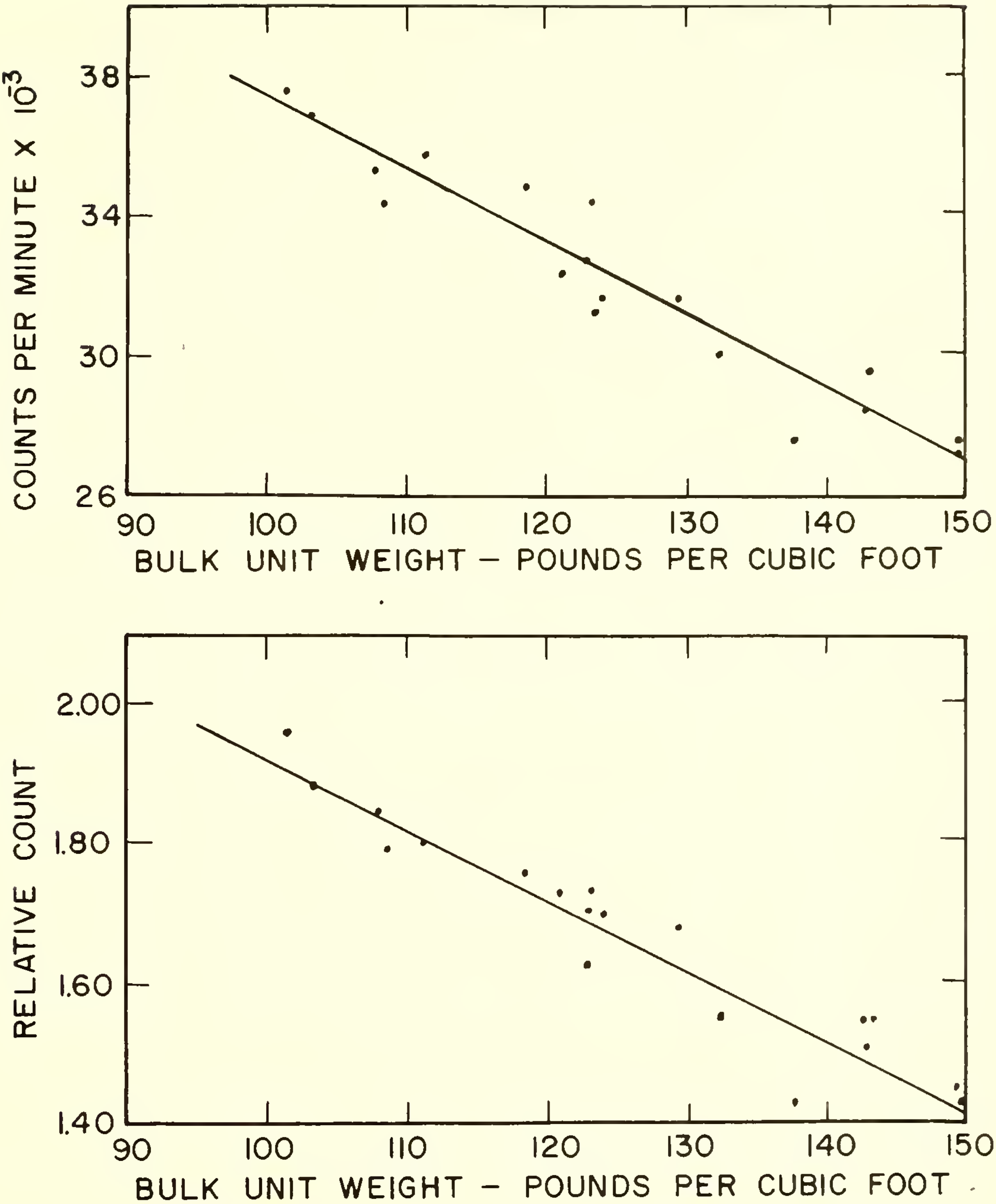

FIG. 26 DENSITY CALIBRATION RESULTS EXPRESSED AS COUNTS PER MINUTE AND RELATIVE COUNT FOR MATERIAL GROUP I— INSTRUMENT B

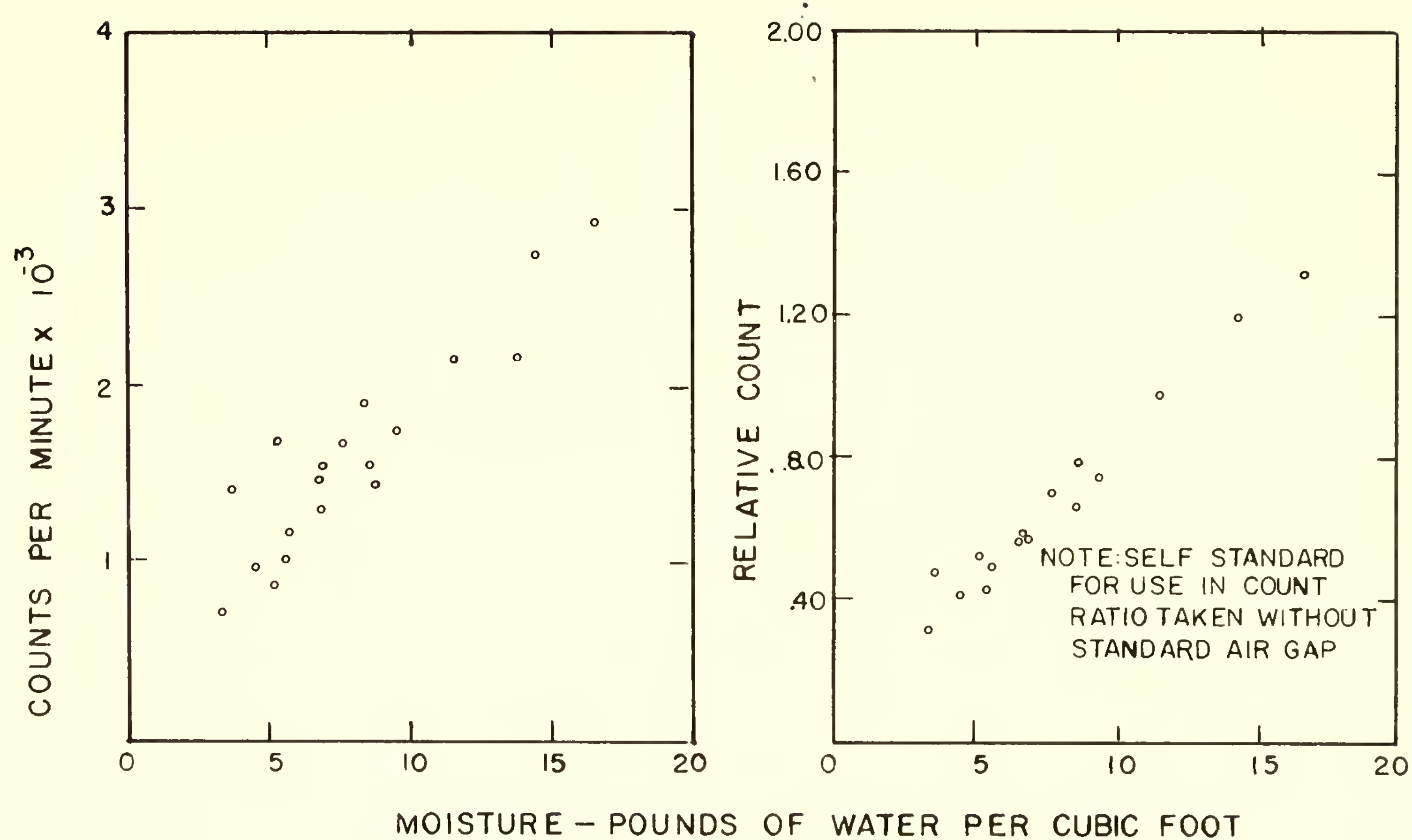

FIG. 27 MOISTURE CALIBRATION RESULTS EXPRESSED AS COUNTS PER MINUTE AND RELATIVE COUNT FOR MATERIAL GROUP I— INSTRUMENT B

Material Group I tests. As a question of uncertainty exists as to the relative amount of variation contributed for each possible cause; the possibility of an inherent error due to substrate interference may be expected.

In conclusion, it can, however, be stated that extreme care must be taken to insure that identical systems surrounding the density and moisture gage are present. If this is not observed and dependency is placed upon the standards taken; regardless of a count ratio procedure or counts per minute analysis, deviations from the true count will be attained.

Use of Leveling Course

When a measuring gage is placed upon a substrate, it is imperative that its position is such as to allow a minimum of voids to form between the top of the soil and the bottom of the gage. Divergence from this procedure will lead to erroneous count readings.

To minimize this effect, it has been suggested that a fine layer of material be distributed on the soil to act as a leveling course between the soil and instrument. To find the effect of the leveling course, a series of readings were taken on the materials in Group II with and without a leveling course. First, density counts were recorded with the gage placed directly on the soil top; with no apparent air gaps visually noticeable. Then a leveling course was uniformly distributed over the substrate as thin a possible. The leveling course used was the exact material type tested crushed to a fine size (pass No. 40 sieve and retained on a No. 200 sieve). Density counts were then obtained in as nearly the identical orientation on the soil as the tests completed without the aid of a leveling course.

A comparison of the relative effects between count ratios for an open graded material (Gradation curve I; 3/4" maximum aggregate size) and a fine crushed material (Gradation curve III; No. 4 maximum aggregate size) are shown for both instruments in Figures 28 through 31. These figures suggest that the leveling course has a larger effect on results for open graded materials than for a fine crushed material. The reason for this is a combination of two facts. First, it is known that for a backscatter device the material closest to the gage will have a greater effect on the particular count registered than material farther away from the gage. Second, for a more open graded material the possibility of segregation of a fine leveling course becomes greater than for the fine material. Therefore, a larger quantity of the leveling course is necessary for open graded materials which consequently affect the count to a greater degree due to its closeness to the instrument.

The primary function of a leveling course is to minimize the effect of air voids upon count readings. If,

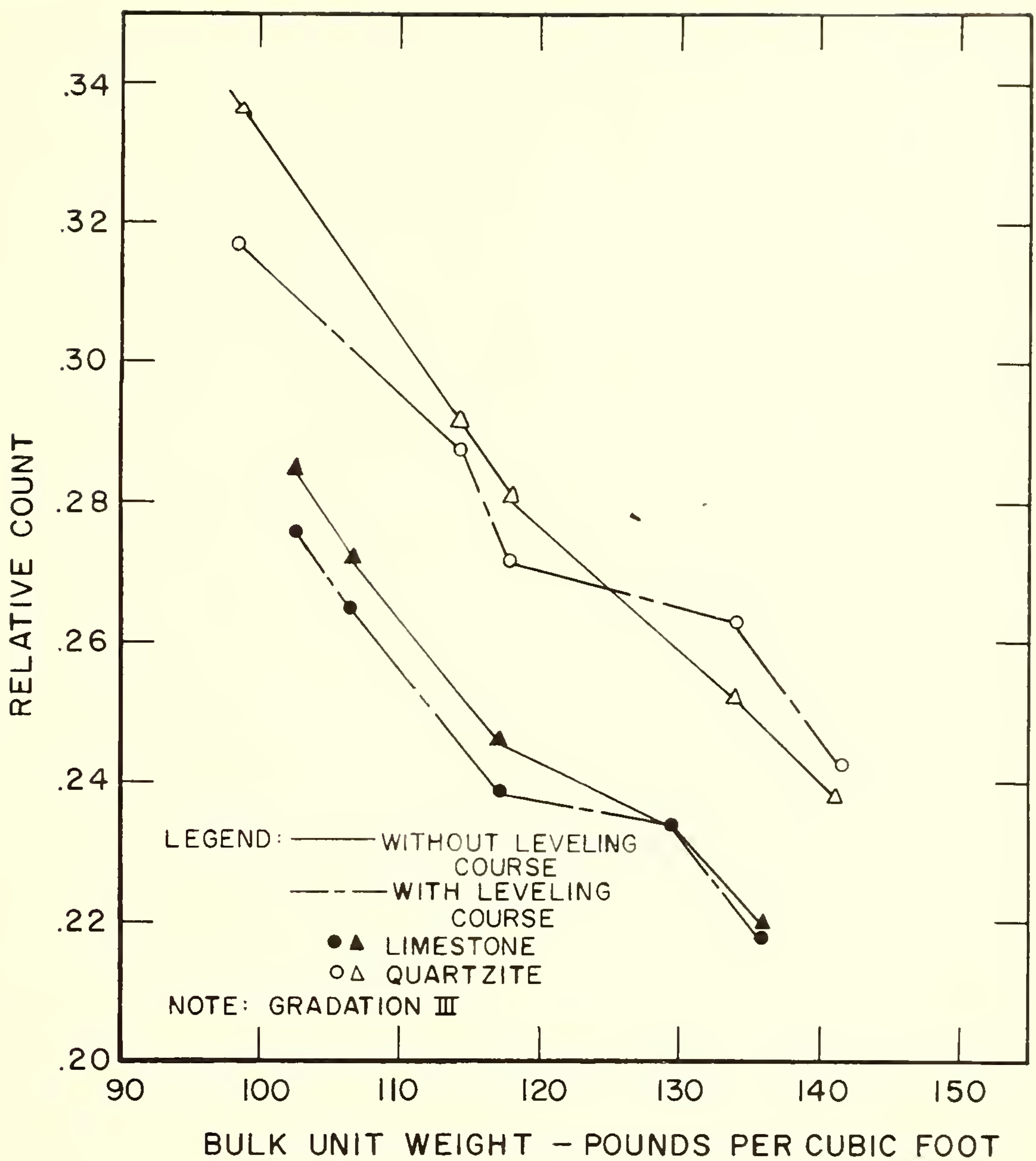

FIG.28 EFFECT OF LEVELING COURSE UPON DENSITY READINGS FOR FINE CRUSHED MATERIAL-INSTRUMENT A

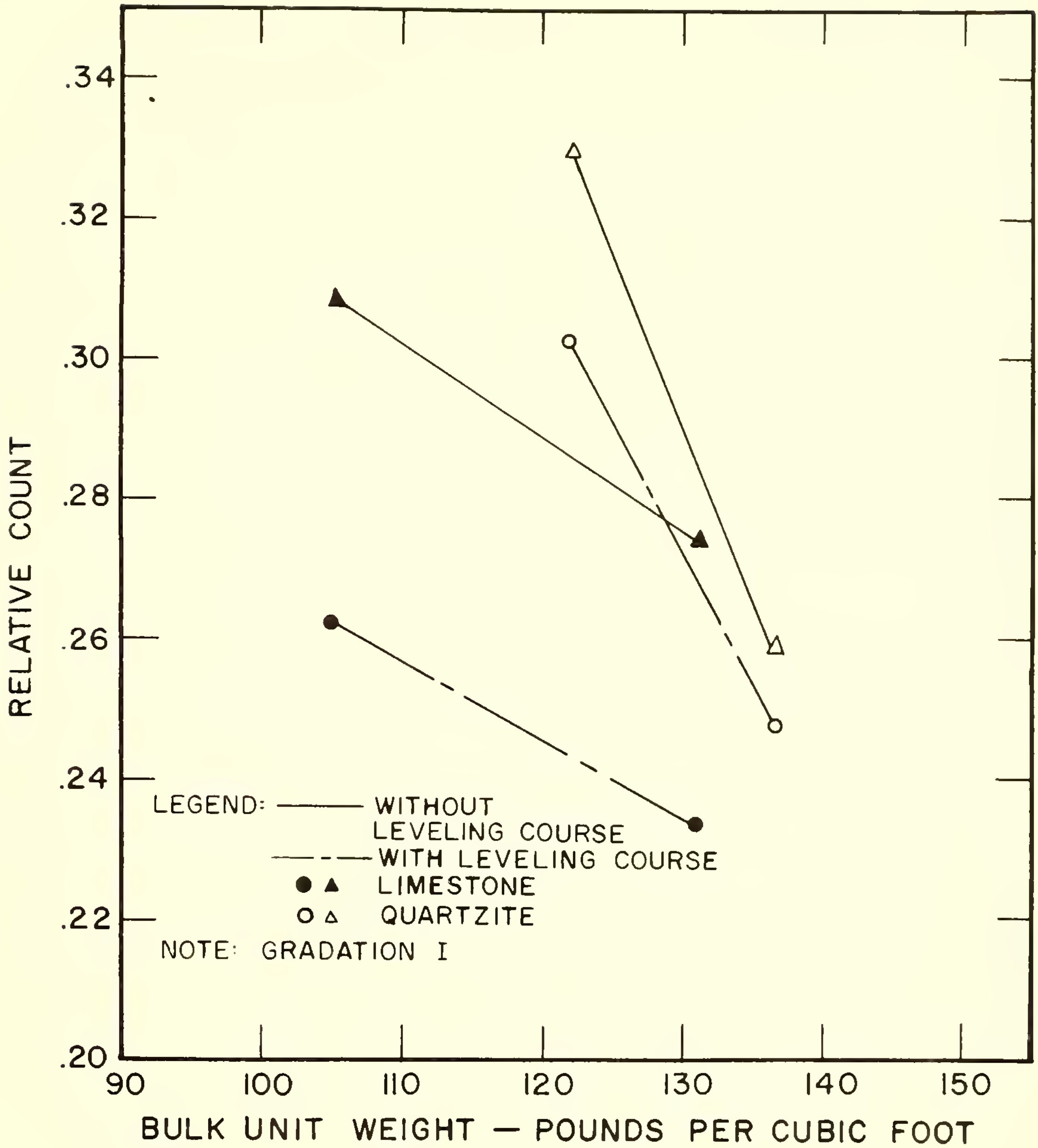

FIG. 29 EFFECT OF LEVELING COURSE UPON DENSITY READINGS FOR OPEN GRADED MATERIAL - INSTRUMENT A

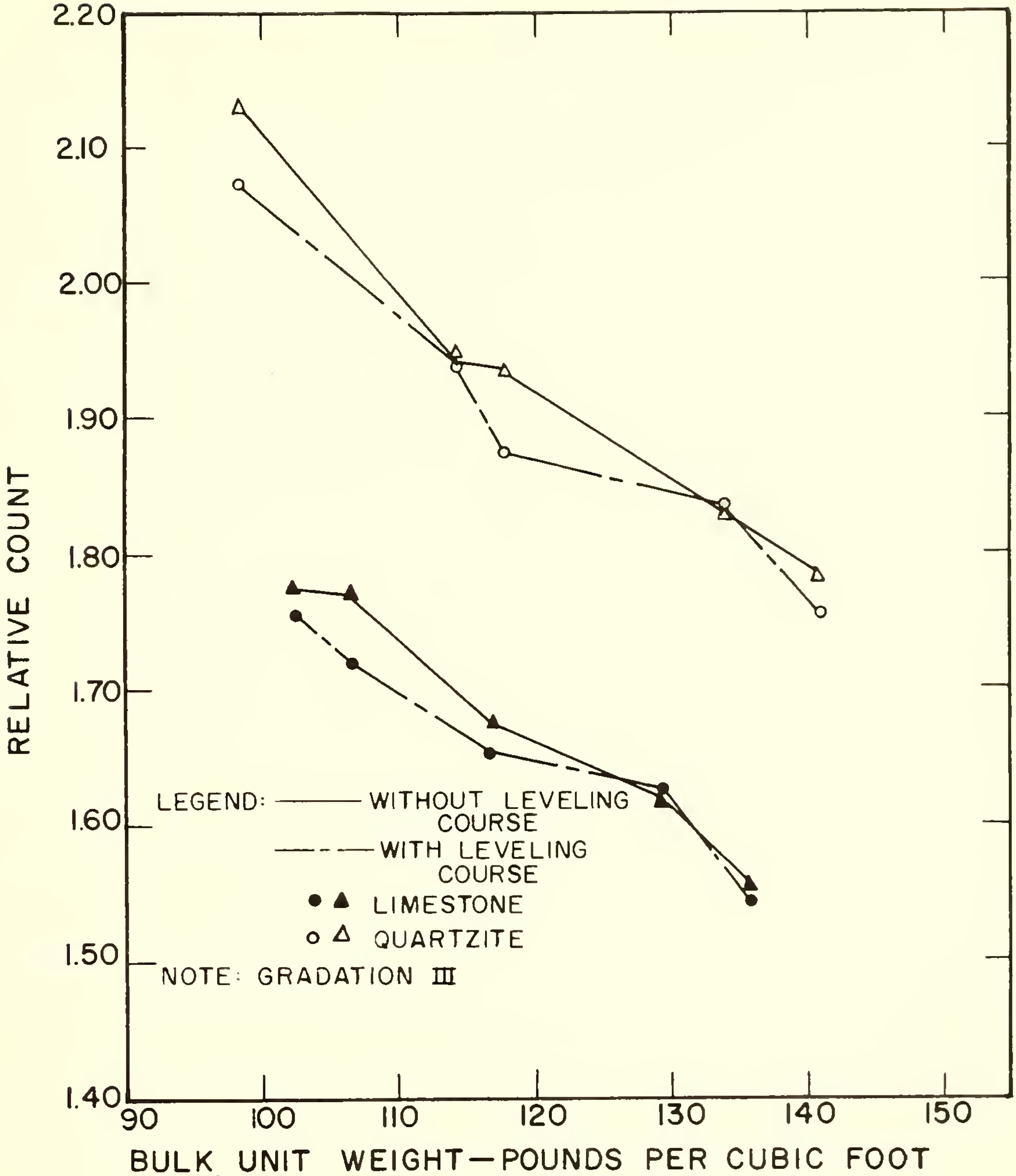

FIG. 30 EFFECT OF LEVELING COURSE UPON DENSITY READINGS FOR FINE CRUSHED MATERIAL—INSTRUMENT B

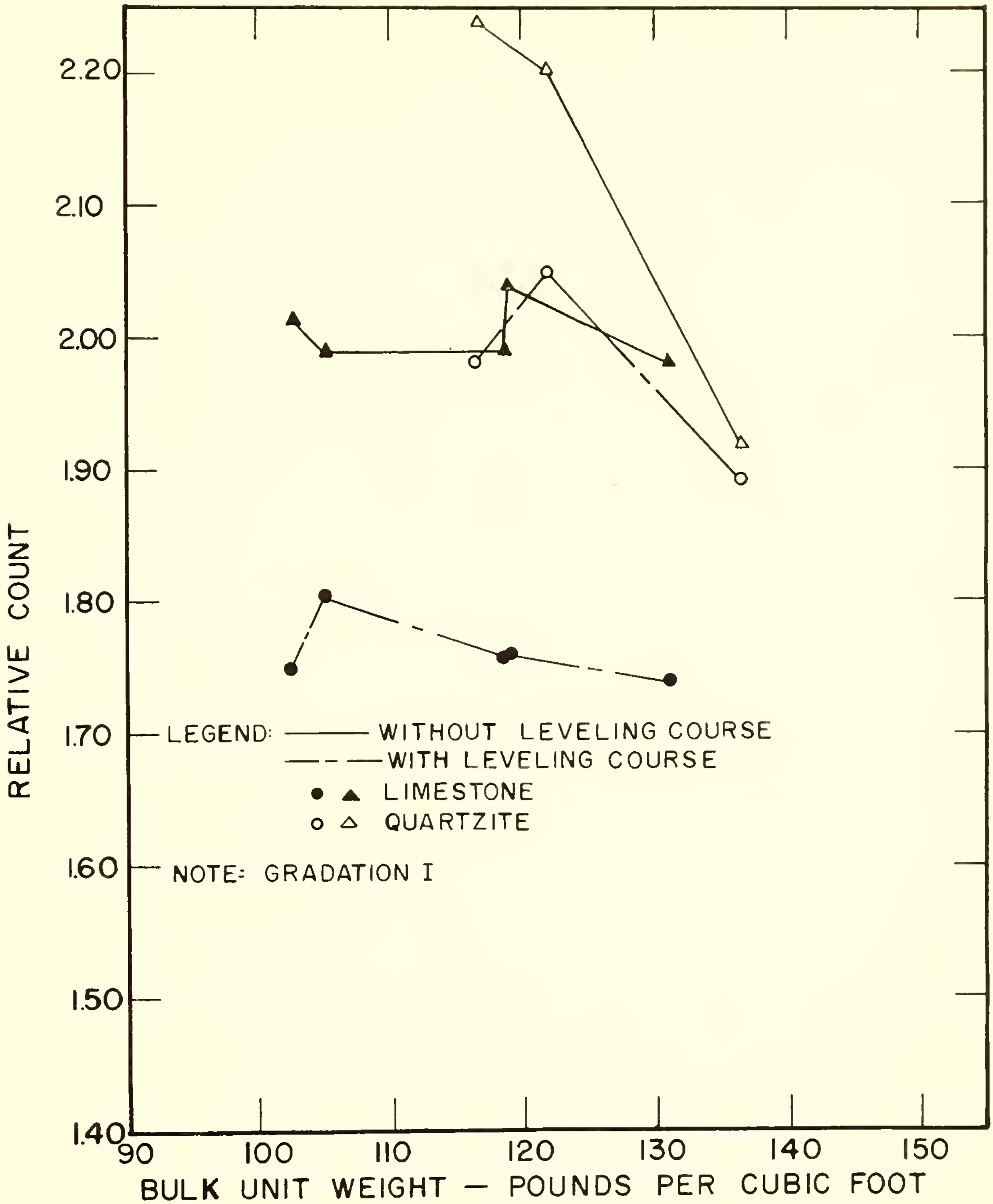

FIG. 31 EFFECT OF LEVELING COURSE UPON DENSITY READINGS FOR OPEN GRADED MATERIAL— INSTRUMENT B

for example, a reading was obtained with the gage in a certain fixed number of orientations without the use of a leveling course, extremities of readings could be found and consequently differences or count ranges obtained. This reading would therefore be a function of the system composed of soil type, homogeneity of the soil at each orientation, and the soil-instrument contact status, or the amount of air voids present under the gage. Consequently, if a leveling course was added and assuming that similar orientations were obtained and therefore similar soil volumes were "seen" by the backscatter radiation; a comparison of the count ranges for both methods of placement would generally indicate the effectiveness of a leveling course.

A graphical analysis of this comparison is shown in Figures 32 and 33. For Instrument A it can be seen that 45 per cent of the readings taken for Material Group II showed a decrease in the count range, or 55 per cent of the readings showed an increase in count range. However, for Instrument B, 75 per cent of the readings showed a decrease in the count range. Consequently, it should be noted that the effectiveness in count range reduction will not always be dependent upon the use of a leveling course, but rather is a function of the instrument type.

Therefore, it can be concluded that the use of a leveling course can have two effects upon an average

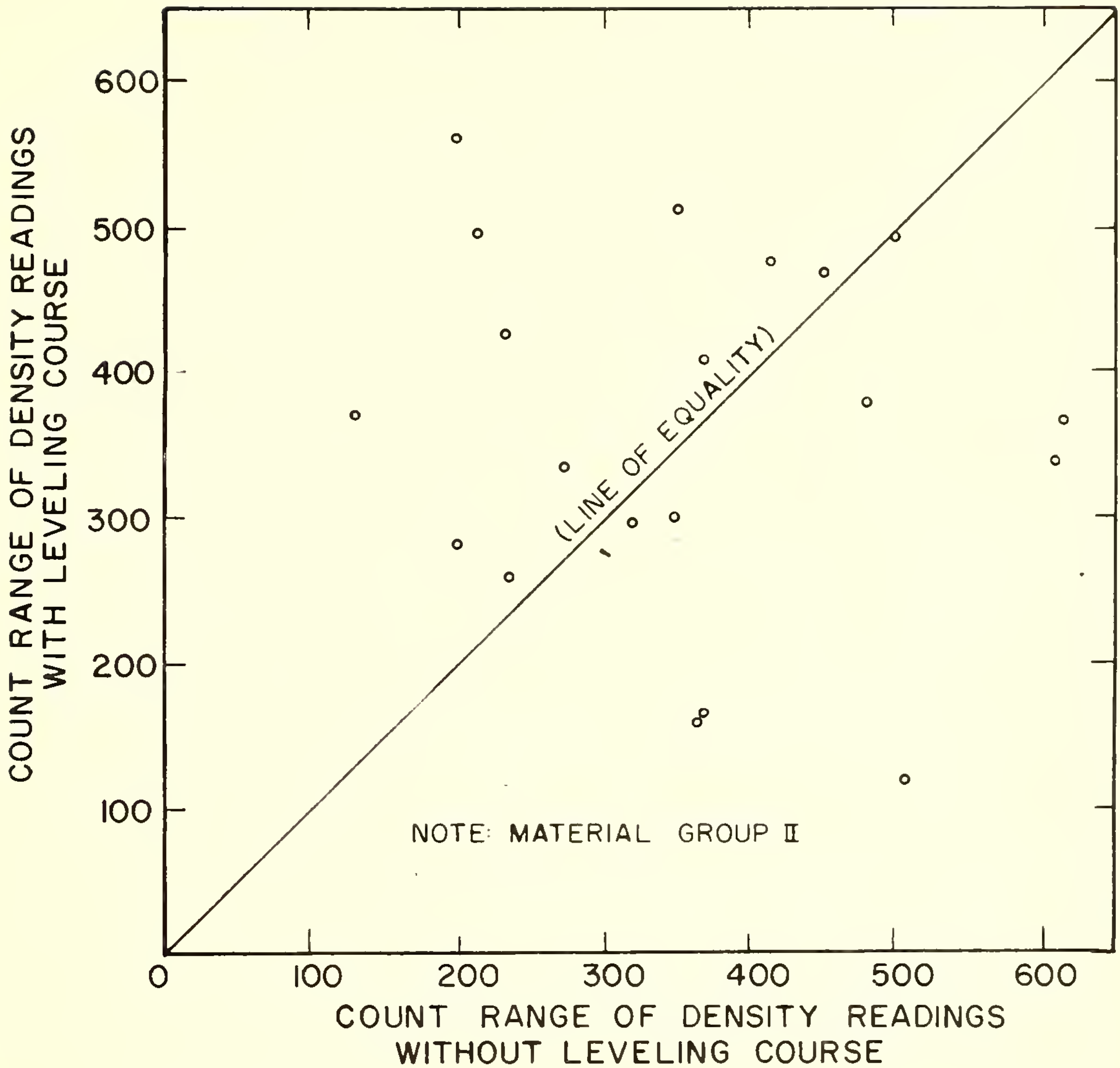

FIG. 32 EFFECT UPON DENSITY COUNT RANGE WHEN USING LEVELING COURSE FOR MATERIAL GROUP II — INSTRUMENT A

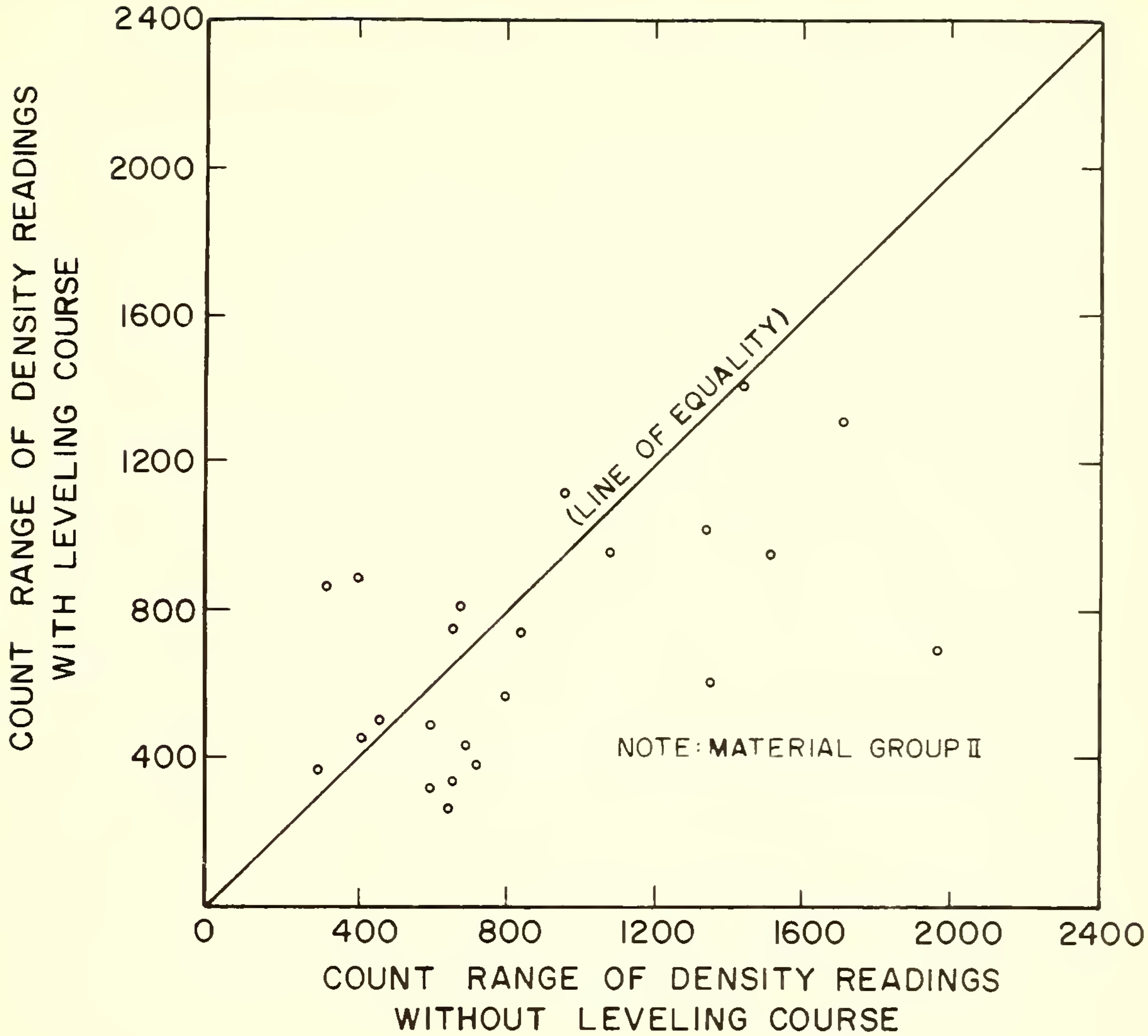

FIG. 33 EFFECT UPON DENSITY COUNT RANGE WHEN USING LEVELING COURSE FOR MATERIAL GROUP II - INSTRUMENT B

reading. First, the introduction of a leveling course will cause larger deviations from density results obtained without a leveling course for a more open graded material than for a finer crushed material. Second, the use of a leveling course in reducing the effect of count ranges is dependent upon the instrument used.

Variations of Density Calibration Procedures

It has been previously stated that the recorded gamma-ray intensity for a nuclear density gage is not only dependent upon the density but it is also a function of the effective depth of penetration.*

It must be assumed that the measured density is an average density of the volumetric zone used in its determination. Consequently, an investigation was completed for Material Group I as to the expected deviations of calibration curves for density determined in a variety of ways.

By utilizing densities determined by the sand cone method and by direct measurments, along with an average of count readings for several consecutive built-up layers and a count reading for the last layer tested, it was possible to establish 4 different calibration curves. Figure 34 represents a summary of these calibration curves for Instrument B.

At densities near 100 pcf, the maximum deviation

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* See Page 38

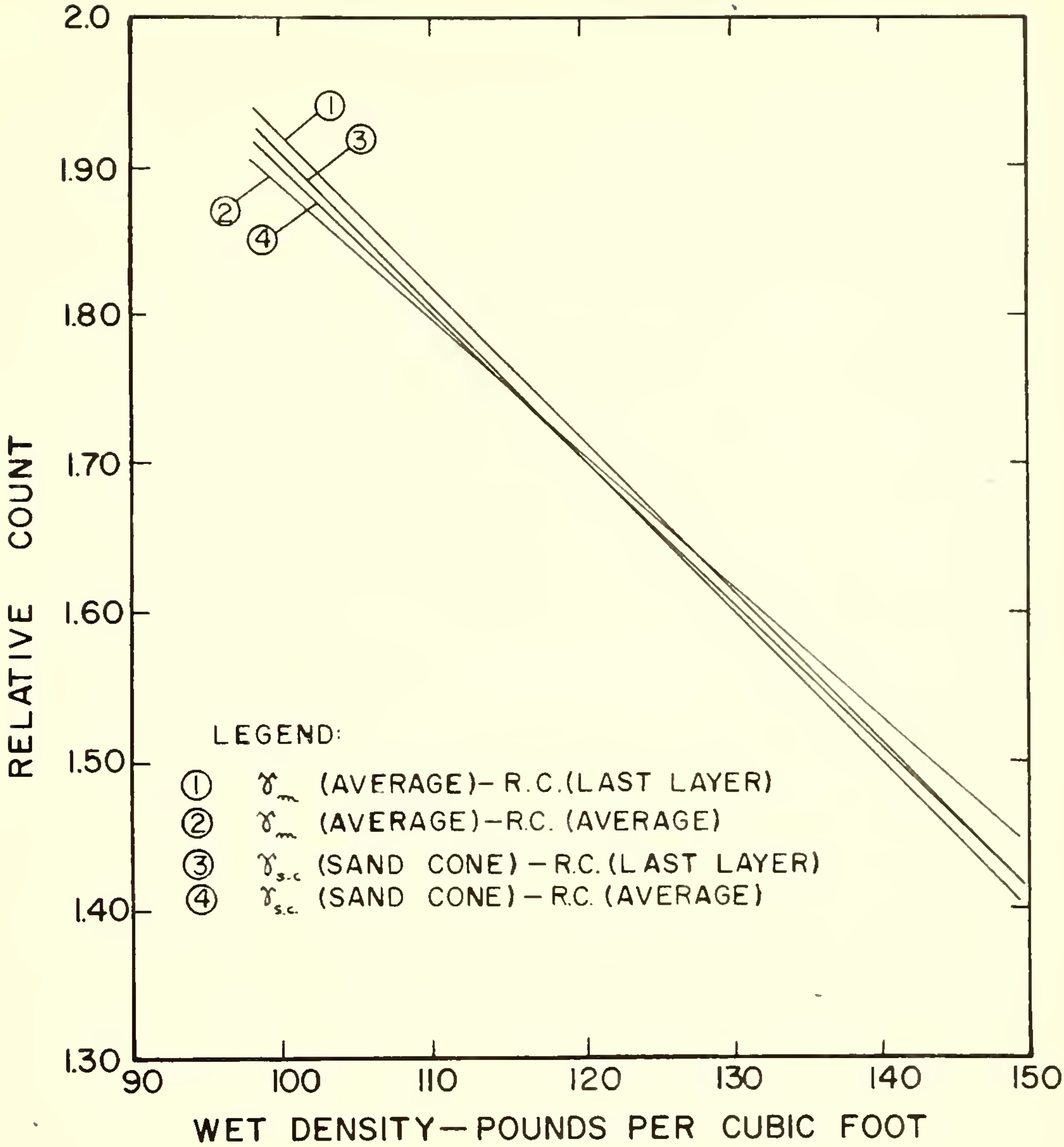

FIG. 34 COMPARISON OF VARIOUS DENSITY CALIBRATION METHODS—INSTRUMENT B

between curves was 3.5 pcf. A deviation of 1.5 pcf occurred for an intermediate density of 120 pcf while at a density of 150 pcf a difference of 4.5 pcf was found to be existant.

It is interesting to note that a comparison of curves determined by the sand cone method versus the count on the last layer showed a consistent deviation of 1.0 pcf.

However, in all eventualities, a resultant calibration curve is the final objective for field employment of the nuclear instruments. Therefore, the various methods of determination and their related divergencies between procedures must be understood.

CONCLUSIONS

The following conclusions apply to the laboratory research program investigating possible parameters that can affect results of density and moisture determination by nuclear radiation techniques.

Substrate Material Properties

1. Both nuclear density gages showed higher counts per minute at a given density for the silaceous material then for the calcareous material.
2. Material type had no effect on the moisture counts per minute relationship for both instruments.
3. Both nuclear density gages showed higher counts per minute for the coarse gradation than for the fine gradation at a given density for the same material type.
4. Moisture in the material mass did not affect the nuclear density results appreciably.
5. The effective depth of penetration for the density gages decreased as the density of the substrate was increased.
6. The effective depth of penetration for the moisture

gages decreased as the quantity of moisture in the substrate was increased.

Instrument Stability

1. The difference between moisture and density self-standards taken at 0°F and 75°F for Instrument A was found to be negligible.
2. Instrument B was inoperative at a temperature of 0°F.
3. Errors attributable to a faulty timer mechanism were negligible throughout the entire testing program for both instruments.
4. Density self-standard readings varied outside the reliable error for Instrument A when tested through an internal battery voltage range of 5.5 volts to 6.5 volts; however, the use of a count ratio analysis reduced the variation to within the allowable limits of error.
5. Moisture self-standard readings for Instrument A were confined to the allowable limits of error when taken through an internal battery voltage range of 5.5 volts to 6.5 volts.
6. Count readings for nuclear density Instrument A obtained upon a concrete block decreased continually throughout the test program time interval.
7. Differences between moisture self-standard read-

ings taken at the commencement and conclusion of the research program were confined to the allowable limits of error for Instrument A.

Instrument Test Procedure

1. Identical physical conditions surrounding the nuclear gages are necessary for accurate self-standard determination.
2. The use of a count ratio will reduce data scatter caused by a variation in instrument stability.
3. The use of a leveling course will cause larger deviations from results obtained without the use of a leveling course for a more open graded material than for a finer crushed material.

SUGGESTIONS FOR FURTHER RESEARCH

The following recommendations are suggested as research projects to help broaden the knowledge of nuclear methods of determining density and moisture.

1. A collective analyzation of data for material type should be undertaken by an agency capable of the immensity of this task to ascertain if these parameters can be quantitatively categorized in their behavior departure from a single calibration curve.
2. Further investigations to determine the effect of grain size distribution on the density calibration curves should be accomplished.
3. The effect of long term usage on count readings and relative counts for a defined standard system should be evaluated.
4. An extensive field project should be undertaken to evaluate the possibility of using nuclear techniques for measuring density and moisture for construction control.

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APPENDIX A

STATISTICAL ERRORS BASED ON A POISSON DISTRIBUTION

Figures 35 and 36 illustrate the various error systems due to a Poisson distribution for Instrument A and Instrument B. In figure 36, a count of 42,250 was taken to be representative of the density self-standard for Instrument A; while for Instrument B, the density self-standard was taken as 19,500 counts per minute.

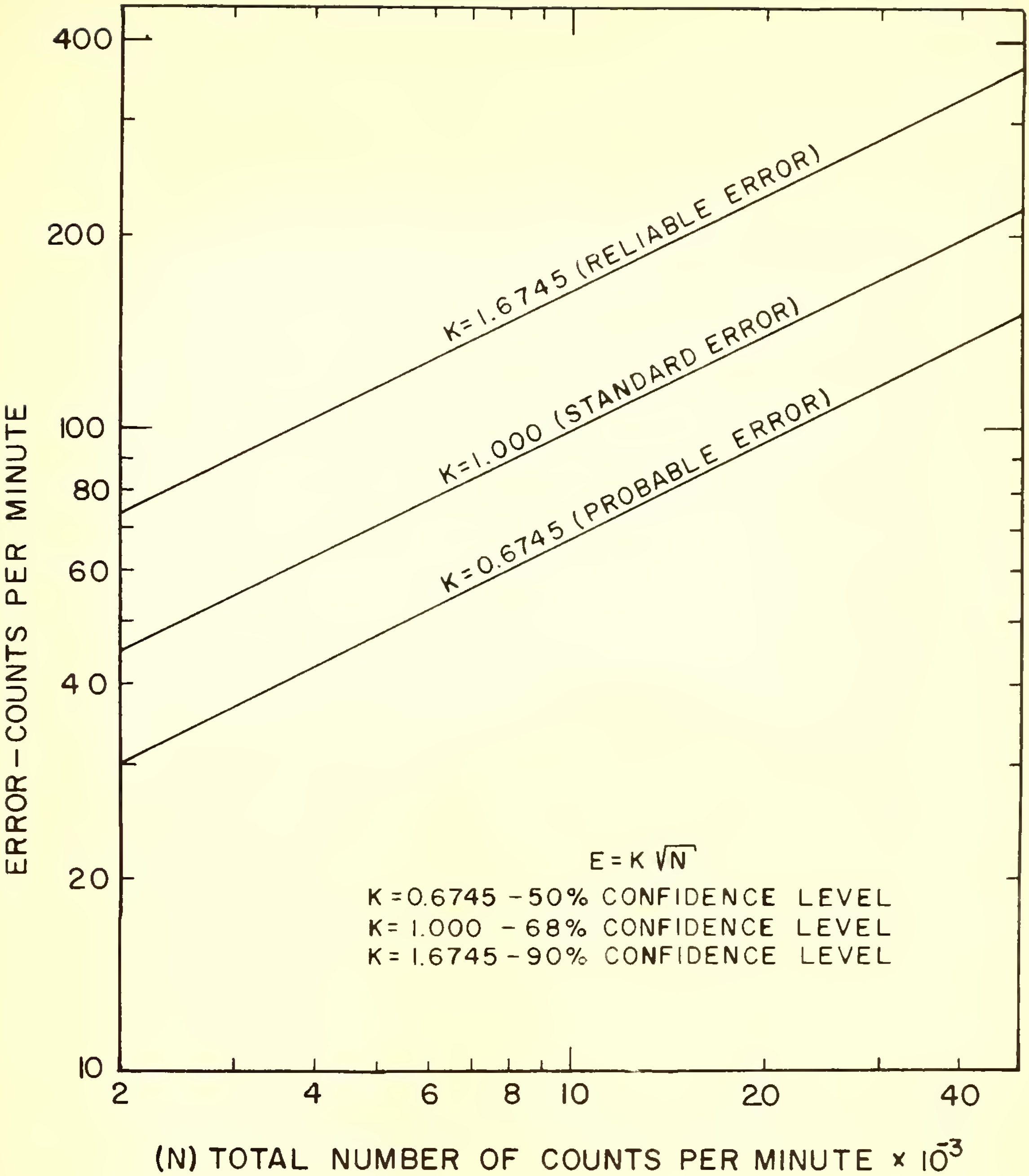

FIG. 35 VARIOUS ERROR SYSTEMS ASSOCIATED WITH RADIATION INTENSITY LEVELS FOR CORRESPONDING CONFIDENCE LIMITS

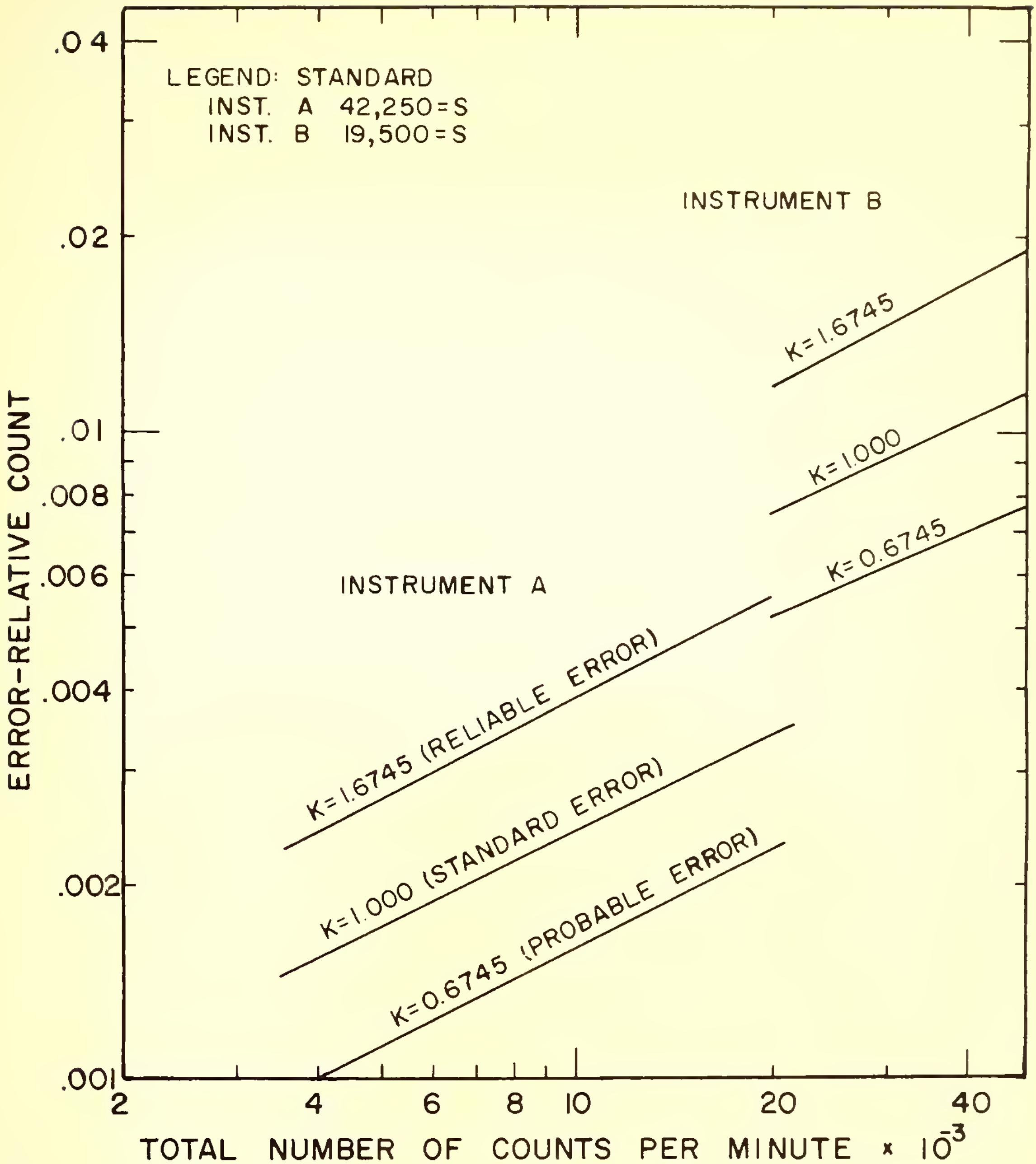

FIG. 36 RELATIVE COUNT ERRORS ASSOCIATED WITH CONFIDENCE LEVELS FOR NUCLEAR DENSITY GAGES OF INSTRUMENTS A AND B

APPENDIX B

SUMMARY OF STATISTICAL ERRORS OF DENSITY TESTS

Table 4 summarizes the statistical errors for all the density tests taken during the research program. Included are tests determined with the use of a leveling course as well as those taken without a leveling course.

TABLE 4

NUMBER OF DENSITY TESTS WITHIN STANDARD AND RELIABLE ERRORS

Instrument A

	Total Number of Tests	Number Within Standard Error	Number Within Reliable Error
1. W.L.C.	21	3	9
2. W.O.L.C.	75	11	36

Instrument B

	Total Number of Tests	Number Within Standard Error	Number Within Reliable Error
1. W.L.C.	24	3	10
2. W.O.L.C.	62	9	16

Note: W.L.C.- With Leveling Course

W.O.L.C. - Without Leveling Course